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Final report

New emission trajectories for new and updated climate scenarios (NEna_ClimS)

by:
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Potsdam Institute for Climate Impact Research (PIK), Potsdam

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Abstract: New emission trajectories for new and updated climate scenarios (NEna_ClimS)

The objective is to provide an overview on the ScenarioMIP process and present preliminary results. The report discusses recent research demands and develops longer-term research needs of a strategic research program for advancing Integrated Assessment Models. Key results are the future temperature developments under a broad set of scenario assumptions. The results are subject to revisions during the further progress of the ScenarioMIP process.

Kurzbeschreibung: Neue Emissionstrajektorien für neue und angepasste Klimaszenarien (NEna_ClimS)

Der vorgelegte Bericht bietet einen Überblick über den ScenarioMIP Prozeß und stellt vorläufige Resultate vor. Der Bericht diskutiert aktuelle Forschungsfragen und entwickelt ein längerfristiges, wissenschaftliches Programm zur Weiterentwicklung der modellbasierten Integrierten Bewertung. Zu den Schlüsselergebnissen gehören wahrscheinlich zukünftige Temperaturentwicklungen für eine weite Spannbreite von Szenarien. Diese stehen allerdings unter dem Vorbehalt, daß diese im weiteren Verlauf des ScenarioMIP Prozesses noch genändert werden.

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List of abbreviations

Abbreviation	Explanation
AFOLU	Agriculture, Forestry and Other Land Use
AR7	Seventh Assessment Report of the IPCC
BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Storage
CBA	Cost-Benefit Analysis
CBDR-RC	Common-but-differentiated-responsibilities-and-respective-capabilities
CEA	Cost-Effectiveness Analysis
CH_4	Methane
CO_2	Carbon dioxide
CMIP	Coupled Model Intercomparison Project
COP	Conference of the Parties (to the UNFCCC)
DACS	Direct Air capture and Storage
DHF	Direct Human Forcer
EW	Enhanced Weathering
ESM	Earth System Model
F-gases	Fluorinated greenhouse gases
FTIP	Federal Transport Infrastructure Plan
GHG	Greenhouse gas
GSAT	Global Surface Air Temperature
GST	Global Stocktake
IAM	Integrated Assessment Model
IAMC	Integrated Assessment Model Consortium
IAV	Impacts, Adaptation, Vulnerability (a community of diverse models for different sectors)
IPCC	Intergovernmental Panel on Climate Change
IMF	International Monetary Fund
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISIMIP	Intersectoral Impact Model Intercomparison Project
LUC	Land-Use Change
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change

Abbreviation	Explanation
MAgPIE	Model of Agricultural Production and its Impacts on the Environment
MIP	Model Intercomparison Project
NDC	Nationally Determined Contributions (in Paris-Agreement)
NPi	National Policies as implemented
N_2O	Nitrous oxide (laughing gas)
OAE	Ocean Alkalinity Enhancement
PIAM	Potsdam Integrated Assessment Modeling Framework
REMIND	Regional Model of Investment and Technological Development
SCC	Social Cost of Carbon
SPM	Summary for Policy Makers
TWh	Terawatt hours (measuring units for energy)
UNFCCC	United Nations Framework Convention on Climate Change
WG	Working Group (of the IPCC)

Summary

Challenges of the Seventh Assessment Report Cycle AR7

This report summarizes the status-quo of the contribution of the REMIND-MAgPIE team to the development of scenarios for ScenarioMIP. The ScenarioMIP process is not yet finished and, therefore, the results are preliminary.

The Plenary of the Intergovernmental Panel on Climate Change aims to shorten the Seventh Assessment Report cycle to inform the Second Global Stocktake in late 2028. This required the scientific community to revisit and revise the original timing of the research plans and the coordination between three major research communities:

1. Integrated Assessment Models (IAMs): this type of models provides a broad set of socioeconomic scenarios with very different climate policies that provide emission and land-use scenarios for the Earth System Models (ESMs) and additional Direct Human Forcers (DHF) for Impact Models (e.g. nitrogen fertilizer, water use, dam building). This community mostly informs Working Group 3 (WG3) of the IPCC on "Mitigation of Climate Change".
2. Earth System Models: ESMs use the climate forcers from IAMs and derive the consequences for climate variables, such as temperature and precipitation. This modeling community mostly informs WG1 of the IPCC on "The Physical Science Basis".
3. Impact Models (IMs): these models use the climate variables of ESMs and the associated DHFs from IAMs to evaluate the consequences on various impact sectors. This modeling community mostly informs WG2 of the IPCC "Impacts of Climate Change".

The original plans were already ambitious because they aimed for three major advances in the integration of the modeling communities:

1. IAMs deliver the emissions and land-use patterns that the ESMs use to run in emission-driven mode. This allows to explicitly capture the effects of land-use change on the vegetation carbon pools and feedback of climate change on the carbon cycle. In previous assessment cycles concentration-driven runs were used that only implicitly included this feedback.
2. The timelines for IAMs and ESMs needed to be tighter to deliver information to the IMs so that the studies and analysis can be conducted in time and published in peer-reviewed Journals for literature cut-off date and the approval of WG2 of IPCC AR7. In AR6 IMs relied on climate information from AR5. Thus, the ambition for AR7 is a fully consistent and integrated scenario analysis for the IPCC assessment. The improved integration of impacts is of high interest for developing countries and emerging economies and, therefore, of great importance for the overall AR7 cycle.
3. IAMs deliver not only the climate forcers to the ESMs but also the associated DHFs to the IMs. Many of these assumptions can be delivered by the IAMs to the IMs. Due to the delays in the interplay between the different working groups it was not possible to make use of this information in a reasonable way. The full assessment of climate impacts needs the DHFs because they vary with the emission scenarios. The more ambitious time schedule aims at a full integration of this information.

Point 1 follows from the request of ScenarioMIP, an Earth System Modelling community MIP within CMIP7, to the IAM community in a narrow sense. The Integrated Assessment Modeling Consortium (IAMC) serves as the conduit to organize the open call and submission process for new scenarios. The REMIND-MAgPIE team at PIK submits scenarios to this process; this report shows selected, provisional results. Point 2 is the ambition for the timeline as the crucial pre-condition for a more integrated assessment in AR7. Point 3 is the ambition of the international

climate research community to provide key information for the assessment of climate change impacts; it is not part of ScenarioMIP.

Thus, the ambition of the IAM, ESM and IM research communities with these three innovations is to provide a more integrated scenario assessment framework and achieve this within a drastically shorter timeline with less targeted funding to support the overall process. The research communities accepted the challenge. The communities coordinated the individual work streams and the interfaces to smoothen, integrate and accelerate the process. For lack of an overarching institutional setting the coordination happened on an ad-hoc basis.

The present report summarizes the contribution of the IAM team at PIK that operates and develops REMIND-MAgPIE to provide new emission and land-use scenarios that will be a key input not only for WG3 on mitigation, but also for WG1 and WG2 (Point 1 above). The report also puts this into a broader perspective by identifying key research questions that need to be addressed by IAMs in the remaining time frame for WG3 and beyond the AR7 cycle.

New Generation of Scenarios for AR7

The ongoing assessment cycle needs new emission and land-use scenarios to derive inputs for ESMs, called climate forcers. These update the SSP scenarios that served as the basis for ScenarioMIP in CMIP6 and AR6 but are outdated by today. The new scenarios are based on a new generation of IAMs with updates on key input assumptions, improved modeling approaches, representing climate policies implemented by governments as of today, and applying new narratives for the policy scenarios and the approximate climate outcomes. In the SSPs 2015 was the start year for the scenarios and climate policies were weak at that time. This is now changed and also a new set of narratives for approximate future temperatures has been developed.

The new scenarios adopt the latest updates on global projections for demographic and economic development. These new input assumptions consider latest developments in fertility rates and migration patterns. This leads for the middle of the road scenario (the updated SSP2) to a population in 2100 that is approximately one billion higher, mostly caused by increases for the countries in the Sub-Sahara Africa region. The GDP developments are now measured with the latest Purchasing Power Parity estimates, consider the economic slow-down related to the COVID 19-pandemic and adjusted near- to long-term expectations to acknowledge recent developments. This leads to a downward revision of growth rate projections in low and low-medium income countries. Governments of key developing and emerging countries, especially India, have more ambitious aspirations for economic development and occasionally criticized the previous growth projections as too low, leading to underestimations about energy and material demands that need be seen in context with equity principles.

The REMIND-MAgPIE model has been developed further in various respects compared with the version used for the SSPs. The most relevant improvements are as follows: The model version has been updated regarding technoeconomic assumptions like renewable investment costs, recognizing their substantially improved performance. The representation of the electricity sector has been improved to better represent the challenges of high shares of variable renewable generation technologies. Also, the potentials for direct and indirect electrification are now explicitly represented by considering key technologies such as heat pumps, electric vehicles and alternative industry processes as well as e-fuels in an explicit bottom-up manner. The representations of demands for material, energy, timber and food have been increased in granularity and the overall demand projections have been revisited and revised based on updates for the socioeconomic drivers of population and income development.

The land-use sector was fully revised and extended to include the forestry sector as well as peatland use and restoration. The aerosol emissions, the CO_2 and non-CO_2 GHG emissions as well as the land-use patterns, the yield rates and carbon densities have been updated to the latest data. The emission reduction potentials for air pollutants and non-CO_2 GHG emissions have been readjusted to acknowledge the latest knowledge. The new model generation is equipped with a broader portfolio of Carbon Dioxide Removal technologies to add Enhanced Weathering (EW), Direct Air Capture and Storage (DACS), afforestation/reforestation and Ocean Alkalinity Enhancement (OAE) to the pre-existing option of Bioenergy with Carbon Capture and Storage (BECCS).

The model version applied here assumes no additional climate change impacts as is required by the ScenarioMIP modelling protocol, which has been assumed in the previous edition of the SSPs as well. The response of increasing temperature on economic activity, i.e. the GDP, and the impact of warming on the agricultural sector can be activated in REMIND-MAgPIE, though.

The ScenarioMIP protocol asks for scenarios that consider existing climate policies to be included and have the same emissions in all scenarios in 2025 with a limited flexibility for emission reduction until the year 2030. This allows the scenarios to be applicable in 2028, when the Second Global Stocktake is scheduled.

The ScenarioMIP protocol asks for a Medium scenario that continues the current level of climate policy ambition in the future. Preliminary results indicate that this would lead to stagnant emissions, similar to the SSP2-45 and a temperature increase well above 2.5°C above pre-industrial levels. This reflects the deficiencies in existing global climate policies to comply with the Paris Agreement. It also asks for a High emission scenario that rolls-back these policies. The REMIND-MAgPIE assumed an SSP3-type narrative for this scenario with higher population, slower economic growth and slow technological advancements. This leads to increasing emissions, but at a much lower level than in the high emission scenario SSP5-85 developed a decade ago. The temperature increase of the new High scenario is therefore reduced to about 3.5°C compared with 5°C for the SSP5-85 scenario.[1] This downward revision reflects the structural changes to energy sector technologies that reduced the long-term reliance on fossil fuels.

At the low-end of the scenario spectrum the most notable novelty is that the ScenarioMIP protocol asks for a scenario (called Very Low with Limited Overshoot) with emissions as low as plausible without threatening sustainability constraints due to excessive use of CDR technologies. This scenario will very likely exceed 1.6°C but the temperature declines continuously after this peak and could fall below 1.5°C by 2100. It builds on a SSP1-type narrative for socioeconomic and technological development and thus has a high degree of income convergence built-in that prescribes developing and emerging economies quickly catching-up with developed countries. Fossil fuel use is strongly reduced declining towards zero by the end of the century. This is facilitated by high efficiency and low demand for energy and bulk materials. Dietary changes towards low meat consumption reduce the pressure on land resources, facilitating afforestation, and also strongly reduce CH_4 emissions to levels that are considered infeasible if only technical mitigation measures would be considered under a default baseline development. The use of bioenergy in this scenario is limited and so is the deployment of BECCS. It is very likely this scenario will not fit the requirements of C1 category of AR6,[2] which has been the benchmark in the First Global Stocktake and was used to derive the global

[1] Increase of global mean surface temperature by 2100 compared with pre-industrial levels.

[2] This refers to the scenario classification of the WG3 contribution to the IPCC's AR6, which classified C1 those scenarios that are below 1.5°C increase of global mean temperature relative to the pre-industrial period with no or low overshoot of less than 0.1°C.

transformation targets. The reason for not meeting the C1 category is that the historic delays in emission reductions until 2025 cannot be undone and, given the current version of the MAGICC model to evaluate the emission pathways, the 0.1°C overshoot margin of the 1.5°C long-term target will be exceeded temporarily.

As an alternative the scenario Very Low after High Overshoot (VLHO) is less ambitious on near-term emission reductions, but engages in strong emission reductions thereafter and deploys all technologies of the CDR portfolio to very large degree and reaches strong net-negative CO_2 emissions in the second half of the 21st century. This scenario will feature a higher peak temperature than the VLLO scenario around mid-century, while the temperature decline will very likely not be sufficient to reach 1.5°C by 2100. This scenario requires very strong political commitment to realize large net-negative emissions.

The Low scenario aims to keep temperature increase well below 2°C, but does also not reach 1.5°C by 2100. It features near-term emissions above the VLLO scenario, but lower than the VLHO scenario. Thus, it illustrates a future with reduced long-term ambition for long-term climate change, but does not rely as strongly on CDR technologies as the VLHO scenario.

An additional scenario, ML, is requested that follows the medium scenario to later branch-off and reduce emissions towards the Low scenario.

This broad set of scenarios will form the basis for additional research that the IAM community will perform after the ScenarioMIP phase is finished. Additional scenarios will explore a broad set of research questions that are, partly, discussed in Chapter 4 of this report and that are key for the WG3 contribution for the IPCC's AR7. A central topic is the equity question and therefore the principle of "Common but Differentiated Responsibilities and Respective Capabilities" as well as international climate finance. This topic is already considered in the ScenarioMIP protocol, but is not the highest priority because ScenarioMIP is mostly concerned with global GHG emission projections rather than the regional allocation of emissions.

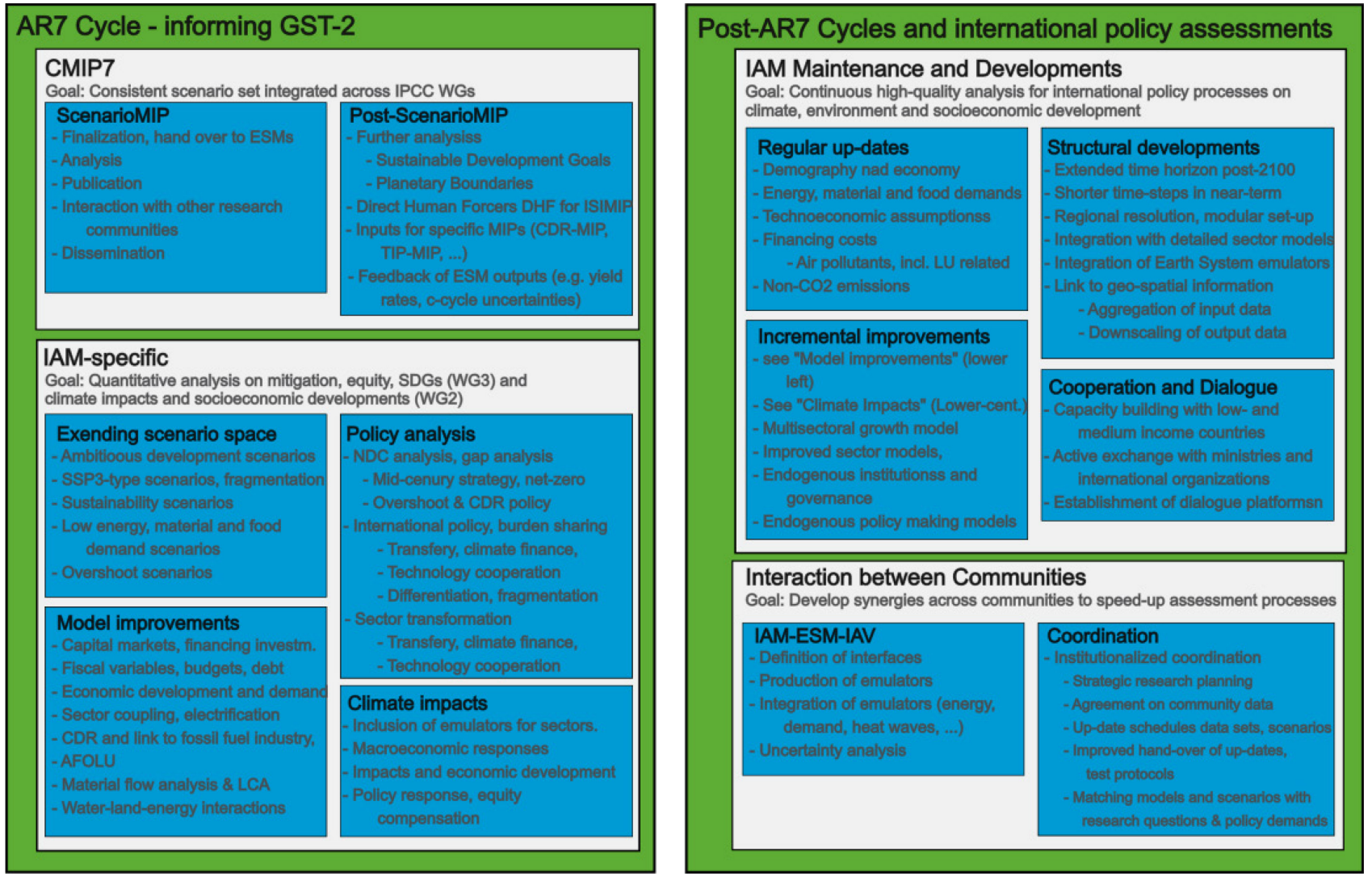
An important concern about ScenarioMIP has been the participation of researchers from countries of the global south (largely non-OECD member countries). The reason is that IAMs are mostly developed and operated at research institutions in the EU, the US and Japan. In preparation of the ScenarioMIP protocol an extensive consultation process has been initiated by the ScenarioMIP steering group and during the open review process of the ScenarioMIP protocol the concern has not been raised (to the best of our knowledge). Also, a research group from the University of Rio de Janeiro participated in the process and contributed to the scenario ensemble with its own IAM.

Next Generation Integrated Framework post-AR7

GST-1 2023 in Dubai invited the IPCC to inform the Conference of the Parties for the second GST and all following GSTs. The framework for scenario development and analysis has to be developed further to enhance the efficiency of the process and deepen the integration of the IPCC working groups in future assessment cycles as shown in Figure 1. The expected alignment of the five-year frequency of GST with the IPCC Assessment cycles would set an important constraint. Within these five year cycles the scientific community would need to

1. improve the work-flows for periodic updates,
2. innovate within the IAM community and
3. improve integration and coordination with the ESM and IAV research groups.

Figure 1: Strategic research requirements for AR7 and post-AR7



Source: own compilation.

The periodic updates need a well-organized schedule to plan for the maintenance work that includes also testing and validation. The periodic updates include data for, among others, energy, emissions, land-use, population, economic development, technologies and resource potentials. This data is provided by different research groups, but the level of coordination is low. Frequently this leads to delays and unplanned revisions that demand personnel and time. Periodic updates need to be time efficient so that teams can spend the time and focus on conceptual innovations and structural improvements.

Innovations in the IAMs benefit from strategic research planning. This helps to better prepare research groups to develop capabilities, orient and reorient focus and specialize on core competences. It also guides research funding and helps to focus research programs. Structural improvements are necessary to keep an IAM relevant. In the coming years the extension of the time horizon beyond 2100 is a key structural improvement. This also needs inputs of scenarios of developments of demography and economics to provide the assumptions that are developed by the dedicated research groups. Moreover, the improved regional granularity is a structural improvement. The PIK team is increasingly asked to develop country specific models; and even sub-national models for states such as India's Utthar Pradesh. In order to implement this efficiently and in a structured way requires basic investments to broaden the modeling platform REMIND-MAgPIE. Once this investment has been undertaken it facilitates the capacity building in partner countries and increase the credibility of the global modeling in REMIND-MAgPIE.

The innovation across the IPCC Working groups touches on the improved interaction from IAM to ESM and to IAV models. If this information pipeline can be speed-up, the objective of closing the loop within an IPCC Assessment cycle comes into reach and could deliver information for the Synthesis report of the IPCC: This would mean that climate and impact emulators are developed and regularly updated early in the cycle so that IAMs can work on fully integrated scenarios with a closed loop where policies are informed by the latest insights from climate and impact.

IAMs can also inform policy processes on socioeconomic development and management of global environmental commons other than climate. This includes long-term economic development, Sustainable Development Goals, public health, trade and innovation as well as Planetary Boundaries, bio-diversity or ocean health. IAMs are versatile tools that can be adjusted and extended to integrate with other disciplines. Therefore, IAMs are not only single-issue information tools limited to climate change policy but can make contributions to a broad range of international policy topics.

Zusammenfassung

Dieser Bericht fasst den aktuellen Stand des Beitrags der REMIND-MAgPIE Gruppe zur Erstellung der ScenarioMIP Szenarien zusammen. Da der Prozess zum Zeitpunkt des Berichts noch nicht zum Abschluss gebracht ist, haben die Ergebnisse noch vorläufigen Charakter.

Das Plenum des Intergovernmental Panel on Climate Change (IPCC) hat vorgeschlagen, die Zeitspanne für den Siebten Sachstandbericht zu verkürzen, um den Zweiten Global Stocktake (GST-2) Ende des Jahres 2028 zu informieren. Das erforderte von den relevanten wissenschaftlichen Disziplinen, dass die ursprünglichen Planungen und Zeitpläne überprüft und überholt werden mussten. Das betrifft die Arbeit und die Koordination zwischen drei maßgeblichen Forschungsgemeinden der folgenden Modellklassen:

1. Integrated Assessment Modelle (IAMs): Sie stellen ein Ensemble von sozioökonomischen Szenarien bereit, dass die Breite der plausiblen zukünftigen Klimatreibern von Emissions- and Landnutzungsmuster abdeckt., die an die Erdsystemmodelle (ESM) als Klimatreiber und die entsprechenden Direkten Menschlichen Treiber (Stickstoffdüngung, Wassernutzung, Staudammprojekte, …) an die Impact Modelle (IM) als Ausgangsdaten weitergereicht werden. Die IAM-Gemeinschaft arbeitet hauptsächlich zu Vermeidungsszenarien und -politiken und informiert damit die Arbeitsgruppe 3 zu „Mitigation of Climate Change“ des IPCC.
2. Erdsystemmodelle (ESMs): Sie verwenden die Klimatreiber der IAMs als exogene Annahmen und evaluieren die Konsequenzen für das Klimasystem (Temperatur, Niederschläge, …) und tragen damit zu den naturwissenschaftlichen Grundlagen für die Arbeitsgruppe 1 des IPCC bei.
3. Impact Modelle (IM): Sie verwenden die Klimavariablen der ESMs und die Direkten Menschlichen Treiber der IAMs, um die Konsequenzen für die ganze Bandbreite der sektoralen Abschätzungen zu evaluieren. Damit wird Arbeitsgruppe 2 zu den „Auswirkungen des Klimawandels“ des IPCC informiert.

Die ursprünglichen Pläne galten schon als ambitioniert, da sie drei wesentliche Fortschritte anstrebten:

1. Die IAMs liefern die Emissions- und Landnutzungsdaten, die von den Erdsystemmodellen entsprechend dem sogenannten emissionsgetriebenen Ansatz evaluiert werden. Im Gegensatz zum herkömmlichen konzentrationsgetriebenen Ansatz erlaubt das die vollumfängliche Abschätzung der Feedbacks zwischen dem Klimasystem und dem Kohlenstoffkreislauf.
2. Die Zeitpläne der IAM und der ESM-Forschungsgemeinden mussten ohnehin verkürzt werden, damit die IM Gruppen ausreichend Zeit haben, um die Analyse der Klimawirkungen vor der Bestätigung des 7. Sachstandberichtes durchzuführen und in Fachjournalen veröffentlichen zu können. In den vorherigen Sachstandsberichten war es wegen allfälliger Verzögerungen nicht gelungen, dass innerhalb eines Berichts alle drei Arbeitsgruppen die Abschätzungen auf Basis eines einheitlichen Satzes von Szenarien und Daten durchführen. Gerade diese Anforderung ist aber von großer Bedeutung für Entwicklungs- und Schwellenländer und damit ist es eine entscheidende Anforderung für die Integrität des gesamten Zyklus an Sachstandberichten.
3. Die IMs sind nicht nur sensitiv gegenüber Veränderungen im Klima, sondern benötigen auch sozioökonomischen Eingangsdaten. Diese Annahmen können – prinzipiell – größtenteils von den IAMs geliefert werden. Wegen der vorherigen Verzögerungen im Zusammenspiel zwischen den Arbeitsgruppen war es nicht möglich diese zusätzlichen Informationen

sinnvoll in den IMs zu verarbeiten. Mit dem ambitionierteren Zeitplan rückt dieser wichtige Schritt der Integration in greifbare Nähe.

Die erste Innovation folgt im engeren Sinn aus der Anfrage des ScenarioMIP. Das ist ein Modelvergleichsprojekt (MIP) im Rahmen des Coupled Intermodel Intercomparison Project (CMIP). Das Integrated Assessment Modeling Consortium (IAMC) hat die Aufgabe angenommen die entsprechenden Szenarien mittels eines offenen Aufrufs an die internationale Wissenschaftsgemeinde zu erstellen und entsprechend zu sammeln und aufzuarbeiten. Das REMIND-MAgPIE Team des PIK trägt zu diesem Prozess bei und reicht auch Szenarien ein. Eine Auswahl vorläufiger Ergebnisse wird in diesem Bericht dargestellt. Die zweite Innovation folgt aus der Ambition der tieferen Integration der Arbeitsgruppen, um so zur höheren Glaubwürdigkeit des Sachstandberichts beizutragen. Die dritte oben genannte Innovation ist nicht Teil des ScenarioMIP im engeren Sinn, und hat im institutionellen Sinn keinen Rahmen, stellt aber die Ambition der internationalen Wissenschaftsgemeinde dar.

Diese drei Innovationen stellen die Ambition der internationalen Klimawissenschaften dar. Sie verlangten schon eine Verdichtung des Zeitplans und wurden mit der Diskussion des IPCC-Plenums zur möglichen Verkürzung des gesamten Zeitplans noch unter weiteren Zeitdruck gestellt. Das hatte auch zur Folge, dass Förderungen nicht zeitnah bereitgestellt werden konnten. Die Wissenschaftsgemeinde hat diese Herausforderung angenommen und ist – bislang – auf einem guten Weg. Die drei Wissensdisziplinen haben die individuellen Arbeitsprozesse besser miteinander abgestimmt und verzahnt, um die Schnittstellen präziser, effizienter und zeitnäher bedienen zu können. Aus Mangel eines übergeordneten institutionellen Rahmens wurden zahlreiche Koordinationsaufgaben improvisiert.

Der vorliegende Bericht fasst den Beitrag des IAM-Teams am PIK zusammen, das das REMIND-MAgPIE Modell entwickelt und betreibt und neue Emissions- und Landnutzungsszenarien bereitstellt. Die Szenarien werden nicht nur einen Beitrag für Arbeitsgruppe 3 zur Vermeidung des Klimawandels leisten, sondern eben auch wesentlichen Input für die anderen beiden Arbeitsgruppen zu den Klimaprojektionen und den Impacts leisten.

Eine neue Generation von Szenarien für den Siebten Sachstandsbericht

Die neuen Emissions- und Landnutzungsszenarien, die sog. Klimatreiber, lösen die ursprünglichen SSP-Szenarien ab, die als Grundlage für den Sechsten Sachstandsbericht dienten, mittlerweile aber veraltet sind. Die neuen Szenarien für ScenarioMIP wurden mit einer neuen Generation von IAMs angefertigt, die neben einer deutlichen Erweiterung und Verfeinerung der Modellierung von Transformationsprozessen außerdem eine Runderneuerung und Aktualisierung der Datengrundlage und der Parameter umfasst. Außerdem nehmen die neuen Szenarien nun den Status-Quo der Klimapolitik als Ausgangspunkt an. In den SSPs war der Startpunkt noch unter der Annahme definiert, dass es im damaligen Basisjahr 2015 noch keinerlei wirksame Klimapolitik gegeben habe. Für die neuen ScenarioMIP Szenarien wurden auch neue Narrative für die zukünftige Entwicklungen und die ungefähren Temperaturpfade entwickelt.

Die neuen Szenarien ziehen die jüngsten Abschätzungen zur sozioökonomischen Entwicklung heran, um die Annahmen zur Entwicklung der Bevölkerung und der wirtschaftlichen Entwicklung zu unterfüttern. Die neuen Bevölkerungsszenarien beinhalten insbesondere Anpassungen der Annahmen hinsichtlich der Fertilitätsraten und der Wanderungsbewegungen. Das führt im mittleren Szenario (SSP2) im Jahr 2100 zu einer Anpassung der Weltbevölkerung um eine Milliarde nach oben, was größtenteils durch Änderungen in Sub-Sahara Afrika getrieben wird. Die Wirtschaftswachstumsprojektionen wurden mit den jüngsten Umrechnungsfaktoren für die Kaufkraftparität erstellt. Außerdem wurden die Auswirkungen der Maßnahmen zur

Bekämpfung der COVID-19 Pandemie in die Datenaktualisierung miteingeschlossen und ebenso Anpassungen an den Wirtschaftswachstumsraten für die nächsten Jahre vorgenommen. Das führt zu einer abwärts gerichteten Anpassung der wirtschaftlichen Wachstumsprojektionen in Ländern mit geringem und gering-mittlerem Einkommen. In zahlreichen Diskussionen haben Wissenschaftler*innen und Regierungsvertreter/berater*innen diese Projektionen in Frage gestellt, da die wirtschaftlichen Entwicklungsambitionen der Länder höher seien. Damit würde auch der Bedarf an Energie und Materialien systematisch unterschätzt werden, was wiederum in Bezug zur Verteilungsgerechtigkeit gesetzt wird.

Das REMIND-MAgPIE Modell wurde seit den SSPs im Jahr 2017 in vielfältiger Weise weiterentwickelt. So wurden die technoökonomischen Annahmen an die jüngsten Entwicklungen und Erwartungen angepasst, um der deutlich verbesserten Wirtschaftlichkeit Erneuerbarer Energien Rechnung zu tragen. Die Erzeugungsseite von Elektrizität wurde in der Modellierung verbessert, um die Möglichkeiten und Herausforderungen durch sehr hohe Anteile Erneuerbarer in geeigneter Weise zu repräsentieren. Auf der Stromverwendungsseite wurden die Möglichkeiten zur Elektrifizierung deutlich verbessert. So werden nun Wärmepumpen, Elektroantriebe und Industrieprozesse in weiten Teilen auf dem Technologielevel dargestellt. Die Nachfrageentwicklungen nach Energiedienstleistungen, Industrieprodukten, Nahrungsmittel, Holz und energetische Biomasse wurden detailliert und empirisch besser unterfüttert. Diese Nachfragepfade sind wiederum mit den neuen sozioökonomischen Treibern konsistent.

Der Landnutzungssektor ist auf den neusten Stand der Daten gebracht und wurde um den Forstsektor als auch die Moorflächenbewirtschaftung erweitert. Insgesamt wurden die Parameter für Emissionen von nicht-CO_2 Treibhausgasen, Aerosolen und Ozonvorläufersubstanzen auf den neusten Stand gebracht. Die aktuelle Modellversion ist mit einem erweiterten Portfolio an Alternativen für die CO_2-Entnahme ausgestattet; dazu gehören: Bioenergie mit CO_2-Abscheidung und -Einlagerung (BECCS), (Wieder-)Aufforstung, Direkte CO_2-Entnahme mit Einlagerung (DACS), Beschleunigte Verwitterung (EW) und Kalkeinbringung in Ozeane (OAE).

Allerdings werden in der vorhandenen Modellversion keine zusätzlichen Rückwirkungen des Klimas auf die sozioökonomischen Systeme angenommen. Das gehört zu den Spezifikationen des ScenarioMIP Prozesses, da die weitere Analyse der Klimaimpacts erst nach den Analysen mittels ESM und IM erfolgen soll. Das ist eine Ähnlichkeit zu den ursprünglichen SSPs.

Das ScenarioMIP-Protokoll verlangt, dass der status-quo der Klimagesetzgebung in den Szenarien berücksichtigt wird. Im Jahr 2025 sollen alle Szenarien dieselben Emissionen aufweisen und bis 2030 soll die Flexibilität zur Emissionsreduktion nur in beschränktem Maße mobilisierbar sein. Damit soll gewährleistet werden, dass die Szenarien im Jahr 2028, also zur anvisierten Zeit der Veröffentlichung der IPCC-Sachstandsberichte und des zweiten Global Stocktake, brauchbar sind.

Das ScenarioMIP Protokoll fragt nach einem Mittleren Szenario (M), das die nationalen Klimapolitiken auf dem gegenwärtigen Anforderungsniveau fortschreibt. Die vorläufigen Resultate zeigen einen stagnierenden Emissionspfad, der dem SSP2-45 ähnelt und damit zu einer Temperaturerhöhung von deutlich über 2.5°C gegenüber dem vor-industriellen Niveau erwarten lassen. Das bestätigt, dass die gegenwärtigen Bemühungen zum Klimaschutz, gemessen an den Zielen des Paris-Abkommens, unzureichend sind. Das Protokoll verlangt außerdem ein Hohes Szenario (H), bei dem die Politiken sogar zurückgefahren werden. Das REMIND-MAgPIE hat für dieses Szenario das SSP3-Narrativ der Regionalen Rivalitäten und des Erstarkens autoritärer Nationalismen angenommen, dass durch höhere Bevölkerung,

langsameres Wirtschaftswachstum und stagnierende Technologieentwicklung charakterisiert ist. Das führt zwar zu steigenden Emissionen, doch bleibt die Entwicklung weit hinter dem SSP5-85 Szenario zurück, das vor einer Dekade entwickelt wurde. Der Temperaturanstieg wurde entsprechend von vormals 5°C auf etwa 3.5°C verringert.[3] Diese Korrektur folgt aus den strukturellen Verbesserungen von Technologien im Energiesektor, die die Abhängigkeit von fossilen Energieträgern nachhaltig verringert haben.

Am unteren Ende des Szenarienspektrums stellt die Anfrage des ScenarioMIP Protokolls nach einem Szenario mit sehr geringer langfristiger Temperaturerhöhung bei geringem Überschreiten (very low with low overshoot, VLLO) eine Neuerung dar. Es stellt die Aufgabe, das Szenario mit den geringsten Emissionen zu identifizieren, dass allerdings Plausibilitätskriterien für die Transformation nicht verletzt und nicht auf übermäßigem Einsatz von Technologien zur Kohlenstoffentnahme beruht. Es ist sehr wahrscheinlich, dass die mittlere Temperatur von 1.6°C zeitweise überschritten wird, gegen Ende des 21. Jahrhunderts besteht allerdings die Möglichkeit, dass 1.5°C Marke unterschritten wird. Es baut auf dem SSP1 Narrativ einer Nachhaltigen Entwicklung mit beschleunigter Konvergenz der pro-Kopf Einkommen der Entwicklungs- und Schwellenländer hin zum Niveau der wohlhabenden Länder auf. Der Verbrauch fossiler Energieträger sinkt rapide, läuft zum Ende des Jahrhunderts aus. Dieser Wandel wird sowohl durch die Erhöhung der Energieeffizienz und Elektrifizierung als auch durch die Verringerung der Nachfrage nach nichtenergetischen Rohstoffen erleichtert. Ein Wandel hin zu einer fleischarmen Ernährungsweise nimmt Druck auf die Landnutzung, was die Wiederaufforstung erleichtert, und die reduziert zusätzlich die CH_4-Emissionen auf Niveaus, die rein mit technischen Vermeidungstechnologien nicht erreichbar wären. Die Nutzung der Bioenergie und damit von BECCS ist begrenzt. Von der Temperaturentwicklung her ist es sehr unwahrscheinlich, dass es in die C1-Klasse des Sechsten Sachstandberichts des IPCC fallen würde.[4] Diese Messlatte definierte die Klasse an Szenarien gegenüber der die Politiken und die Transformationsziele des GST-1 verglichen wurden. Der Hauptgrund für dieses Verfehlen liegt am Überschreiten der maximalen Erwärmung von 1.5°C zuzüglich der 0.1°C der temporären Kulanz. Diese Abschätzung beruht auf der vorläufigen Version des einfachen Klimamodells MAGICC. Dieses Modell wird im Verlauf des Siebten Sachstandsberichtes auf den Stand der neuen ESM gebracht, die aber erst noch mit den neuen ScenarioMIP Inputs getrieben werden müssen. Diese Aussage muss also mit diesem Vorbehalt betrachtet werden.

Das Szenario mit geringer Temperaturerhöhung aber hohem Überschreitungsgrad (very low with high overshoot, VLHO) ist bei den kurzfristigen Emissionen weniger ambitioniert und soll gegen Ende des 21 Jahrhunderts die 1.5°C näherungsweise wieder erreichen. In diesem Szenario erfolgen die Emissionsreduktionen erst später und darüber hinaus werden die Technologien zur CO_2-Entnahme massiv hochgefahren, so dass die Netto-Emissionen von CO_2 stark negativ werden. Dieses Szenario unterschreitet die Langfristgrenze von 1.5°C nicht, verlangt aber ein starkes Maß an politischer Selbstbindung um langfristig das Ambitionsniveau zu erhöhen und die Zielmarke nach 2100 zu erreichen.

Das niedrige Szenario (Low, L) beschränkt den Temperaturanstieg auf deutlich unter 2°C aber strebt keine zusätzlichen Anstrengungen an, die 1.5°C Marke bis 2100 wieder zu unterschreiten. Die kurzfristige Emissionsentwicklung liegt zwischen dem VLLO und dem VLHO Szenario. Damit schraubt das L Szenario das Ambitionsniveau gegenüber dem VLLO Szenario insgesamt

[3] Increase of global mean surface temperature by 2100 compared with pre-industrial levels.

[4] Die Bezeichungen C1 bis C8 bezieht sich auf die Szenarienklassifikation der Arbeitsgruppe 3 des IPCC im Sechsten Sachstandsbericht. C1 bezeichnet die Menge aller Szenarien, die die 1.5°C Marke nicht oder nur mit einer geringen Kulanz von 0.1°C überschreiten.

herunter und bereitet auch nicht – wie im VLHO Szenario - langfristig die großskalige Entwicklung der Technologien zur CO_2 Entnahme vor.

Es gibt außerdem ein Szenario, das zunächst dem M Szenario folgt und erst zu einem späteren Zeitpunkt die politischen Maßnahmen erhöht, um die Verzögerungen wieder wett zu machen und die langfristigen Ziele des L Szenarios zu erreichen.

Diese Szenarien werden den Kern für weitere Forschungen der IAM-Community bilden, sobald diese Phase des ScenarioMIP Prozess abgeschlossen sein wird. Eine sehr viel größere Zahl von Szenarien wird notwendig sein, um die vielfältigen klimapolitischen Fragen beantworten zu können, die zum Teil in Kapitel 4 besprochen werden und für den Beitrag der Arbeitsgruppe 3 zum Siebten Sachstandbericht relevant sind. Die nachfolgende Abbildung 2 stellt diese Innovationen auf der linken Hälfte schematisch dar. Von ausschlaggebender Bedeutung werden Fragen zur Klimagerechtigkeit und damit zum Prinzip der *Common but differentiated responsibiltities and respective capabilities* als auch der der internationalen Finanzierungsinstrumente sein. Diese Fragen haben im ScenarioMIP eine nachgeordnete Rolle gespielt, da es hauptsächlich um globale Emissionen geht und weniger um die Verteilung von Emissionsrechten und Vermeidungslasten.

Im Vorlauf zum ScenarioMIP Prozess war die unterproportionale Teilnahme von Forscher*innen aus dem sogenannten globalen Süden kritisiert worden. Anlass dafür ist, dass IAM im Wesentlichen an Forschungseinrichtungen in den USA, der EU und Japan entwickelt und betrieben werden. Im Entstehungsprozess zu ScenarioMIP wurde ein ausgiebiger Konsultationsprozess durchgeführt. Im anschließenden Begutachtungsprozess zur Veröffentlichung des ScenarioMIP Protokoll wurde dieser Punkt (unseres Wissens nach) nicht wieder aufgeworfen. Im Verlauf des Prozesses wurden Szenarien durch das COFFEE Team von der Universität Rio de Janeiro eingereicht, womit nun auch die aktive Teilnahme eines Forschungsteams von außerhalb der OECD sichergestellt ist.

Neue Generation von Integrierter Szenarioanalyse für kommende Sachstandsberichte

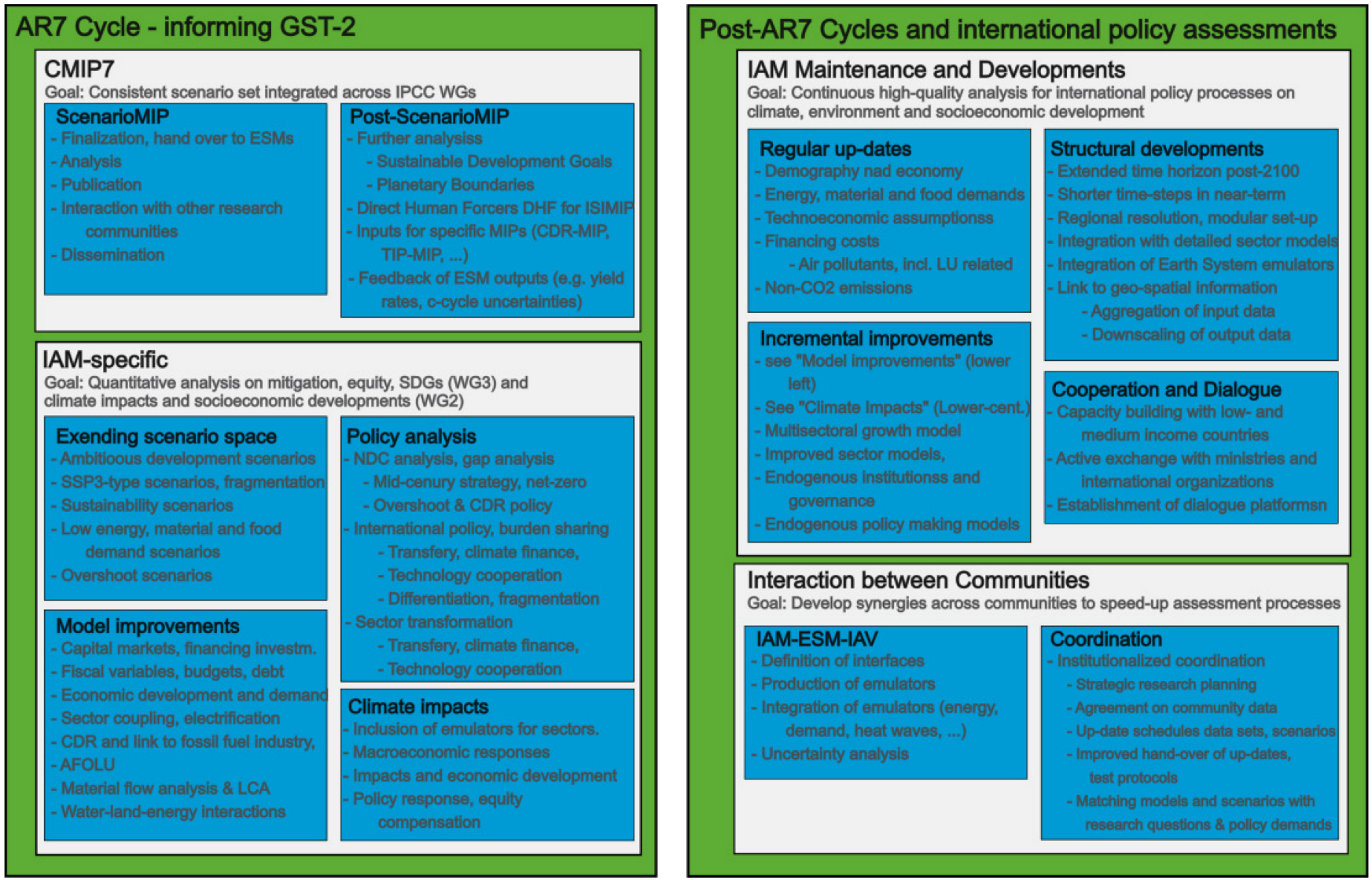
Im Abschlussdokument der ersten Globalen Bestandsaufnahme wurde der IPCC eingeladen, für den kommenden und die folgenden Bestandsaufnahmen relevante Informationen und Analysen bereitzustellen. Für die kommenden Zyklen wird es einen vertieften und besser verzahnten Rahmen für die Szenarioanalyse brauchen; in der nachfolgenden Abbildung (Figure 2) sind die Erfordernisse in der rechten Hälfte schematisch dargestellt. Dafür wird eine bessere Koordination und bessere Effizienz benötigt, um die Arbeiten innerhalb der fünf-jährigen Zyklen zu bewerkstelligen, um so die unabdingbaren wissenschaftlichen Grundlagen für die Verhandlungen für die NDCs und die GSTs breitzustellen. Benötigt wird insbesondere:

1. Beschleunigung der Arbeitsschritte für die regelmäßig anfallenden, umfassenden und qualitativ hochwertigen Updates der Modelle.
2. Umsetzung von Innovationen in den IAMs, um den erweiterten Anforderungen gerecht zu werden.
3. Verbesserte Integration und Koordination der IAM-Gemeinde mit den ESMs und IMs.

Die periodischen Updates verlangen koordinierte Zeitpläne, die ausreichend Zeit für Implementierungen, Tests und Validierung berücksichtigen. Diese Updates beziehen sich auf Daten, die über verschiedene Disziplinen mit vielfältigen Bezügen zu IPCC-Arbeitsgruppen hinweg betreffen: Bevölkerungs- und Wirtschaftsentwicklung, Technologien und Ressourcenabschätzungen, Energie, Emissionen und Landnutzungsmuster. Bislang ist der Grad an Koordination gering, was häufig zu Zeitverlusten bei enormem Ressourceneinsatz führt. Eine Erhöhung der Effizienz dieser Prozesse verkürzt die Zeitspannen für unerlässliche

Arbeitsschritte und die freiwerdenden Ressourcen können anderweitig eingesetzt werden (Modellinnovationen und strukturelle Verbesserungen).

Figure 2: Strategischer Forschungsbedarf für den AR7 und nachfolgende Sachstandsberichte



Source: Eigene Zusammenstellung.

Innovationen in IAMs können durch strategische Planung erleichtert werden, indem Forschungsgruppen besser vorbereitet sind und indem sie entsprechende Kapazitäten und bedarfsgerecht Kernkompetenzen entwickeln. Die strategische Planung kann auch die Erwartungen der Forschungsförderung anleiten. Die strukturellen Veränderungen der Modelle, wie die Verlängerung des Zeithorizontes über das Jahr 2100 hinaus, sind notwendig, um der Langfristigkeit des Klimaproblems gerecht zu werden. Das verlangt nicht nur die Verbesserung in den IAMs, sondern auch längere Prognosezeiträume auf Seiten der sozioökonomischen Treiber der Bevölkerungs- und Wirtschaftsprojektionen. Ähnlich verhält es sich mit der höheren regionalen Auflösung. Das PIK-Team wird immer häufiger von nationalen und sogar subnationalen Entscheidungsträgern aus Entwicklungs- und Schwellenländern zu Modellierungskapazitäten gefragt; z.B. Utthar Pradesh in Indien. Um diesen Anforderungen in effizienter Art und Weise gerecht zu werden, ist ein umfassendes Investment notwendig. Damit könnte das REMIND-MAgPIE Team einen strukturierten Beitrag zum Aufbau von Modellierungskapazitäten in Entwicklungs- und Schwellenländern leisten und die Glaubwürdigkeit der globalen Modellergebnisse von REMIND-MAgPIE bei Entscheidungsträgern verbessern.

Die Innovationen beziehen sich auch auf die vertiefte Integration der IAM mit den ESM und IM Gemeinden. Insoweit die bestehenden Interaktionen ausgebaut und effizienter gestaltet werden können, wird Zeit frei, um den Ansatz den Kreis zwischen den Modellen zu schließen, damit die Reaktion auf die Klimaimpacts voll endogenisiert werden kann. Den Kreis zu schließen, bedeutet einerseits, dass die Ursache-Wirkungskette von den Emissionen zu den Klimawirkungen geschlossen wird, und andererseits die Informationen darüber in vorbeugenden Politikmaßnahmen berücksichtigt werden. Zu diesem Zweck müssen die disziplinären Modelle in sog. Emulatoren vereinfacht werden, die in den nachfolgenden Zyklen an die verbesserten IAMs angepasst werden müssen.

IAMs sind auch geeignet, um weitere Politikprozesse im Bereich der Entwicklungs- und Umweltpolitik zu informieren. Dazu gehören unter anderem ökonomische Entwicklung, Gesundheitswesen, Handel und Innovation wie auch Biodiversität und Ozeane. IAMs sind analytische Werkzeuge, die flexibel angepasst und erweitert werden können. Damit sind IAMs nicht nur auf das engumgrenzte Thema des Klimawandels beschränkt, sondern können in vielen weiteren Bereichen einen Beitrag zur Politikberatung leisten.

1 Introduction and Background

1.1 Objectives, scope and structure of the report

This final report summarizes provisional progress and results of the NEna_ClimS project. It provides an overview of the ScenarioMIP process and the progress of PIK's contribution to the process. Moreover, it outlines open research questions, how to address them in the ongoing Assessment Report Cycle of the IPCC, and how to prepare for future assessment cycles. NEna_ClimS partly supported the development of the new climate scenarios as part of the contribution of PIK to the ScenarioMIP process. This process is part of the CMIP7 project under the umbrella of the World Meteorological Organization (WMO).

In a narrow sense, ScenarioMIP comprises the delivery of the climate forcers of emissions and land use for the Earth System Models within CMIP7 for the evaluation of future climate development for vastly different assumptions about climate policies and socioeconomic development. In a broader sense, these scenarios are the essential starting point for research to inform the Seventh Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and, thus, the Second Global Stocktake (GST-2) in 2028. The ongoing ScenarioMIP process is also the essential initialization for future Assessment Report cycles that provide scientific analysis for the IPCC that, in turn, informs the UNFCCC negotiation process to implement the Paris Agreement. For effective continuation, we propose a strategic research plan for the AR7 cycle and subsequent IPCC assessment cycles as well as other assessments of global environmental change and socioeconomic development.

The proposed schedule of the Seventh IPCC assessment cycle is reduced to only five years in order to run in tandem with the political cycles of NDC/GST updates. This creates unprecedented momentum within and between the research communities to coordinate better, integrate deeper and implement faster. Many mechanisms within the overall process have started to move towards acceleration and qualitative improvement. This momentum can be used in the coming years to improve the research framework by deepening the integration of research communities and better coordination of research processes. This requires more transparency and coordination, which facilitates openness of the process and increases replicability and credibility of the research. The strategic research plan in Chapter 7 lays out the requirements to achieve an improved process in the future.

A crucial Leitmotif for the improvements in model and scenario development is the continuous improvement of equity and justice considerations in the assessment framework to not only inform climate change policies in a narrow sense, but also derive information relevant for a broader set of international policy processes such as the Sustainable Development Goals (SDGs). These knowledge gaps are identified in Chapter 7. Interfacing with the Impact model community is also relevant for equity issues. This comprises the improved quantification of Direct Human Forcers (DHFs), such as nitrogen fertilizer use, water demands, etc. (e.g., Müller-Schmied et al. 2021). These DHFs are explicitly requested by the IAV community (Frieler et al. (2024) via the ISIMIP consortium[5] that is operated at PIK. Although many issues related to climate inputs and DHFs for IAV modeling may appear rather technical, the timely preparation and analysis of these outcomes are a key input for the IPCC AR7 and of great interest for many countries (especially for developing countries).

The ScenarioMIP process defines a small set of scenarios that will be evaluated with ESMs. The climate outcomes will provide crucial information for WG1 of the IPCC on the climate sciences.

[5] ISIMIP stands for Intersectoral Impact Model Intercomparison Project.

The climate outcomes along with the DHFs will be used by the IAV community that is supposed to inform WG2 of the IPCC on Impacts and Adaptation. The scenario set will also be important for the assessment of mitigation pathways and policies for WG3 of the IPCC, because it can serve as a basis to choose the benchmark against which policies and policy proposals are compared. This would continue past practice as e.g. GST-1 has chosen the C1-type scenarios of IPCC AR6 WG3 as the reference against which measures have been compared. However, the limited number of scenarios of ScenarioMIP will only be appropriate to address a limited number of policy relevant research questions that the IPCC will assess. Consequently, more research and additional scenarios will be performed for AR7 and the Second Global Stocktake after the IAM teams have delivered the ScenarioMIP scenarios.

The report is structured into six main Chapters. First, after providing some background of ScenarioMIP in this introduction, we introduce the main classes of IAMs, the modes of policy analysis and the relationship to policy implementation (Chapter 2). Second, we provide an overview of the narratives and specifications of the scenario set of ScenarioMIP (Chapter 3). Third, we review the literature of scenarios used in AR6 and extend it by incorporating more recent scenarios to identify key knowledge gaps that strategic research efforts need to fill (Chapter 4). Fourth, we provide a short introduction of the REMIND-MAgPIE model that the PIK team uses for the scenarios (Chapter 5). Fifth, we introduce the preliminary set of scenarios and compare them with previous scenarios (Chapter 6). Sixth, we discuss the scenario results against the backdrop of the knowledge gaps and derive priorities for strategic research efforts (Chapter 7).

1.2 General background information on the status-quo

The development of the scenarios by the Integrated Assessment Models (IAMs) that inform the climate forcers for the Earth System Models (ESMs) is in the final stages as this report is prepared. Therefore, the scenarios still have a preliminary character. Also, this report only presents scenarios prepared with the REMIND-MAgPIE model. It cannot present preliminary and unpublished results from the other modeling teams.

It must be noted that the use of the term global mean temperature (GMT) anomaly is on the one hand constitutive for the specifications of the scenarios, but also subject to revisions within the ScenarioMIP process. We use here the latest version of the MAGICC model. This model version is at the start of a multi-staged update cycle, the updates are expected to include a new model implementation, updates and revisions of historic data and – last, but not least – validation against the new results of the ESMs that will be fed with climate forcers developed in ScenarioMIP. Therefore, the temperature outcomes presented here, are by nature of the ScenarioMIP process preliminary and are subject to changes as the CMIP7 cycle progresses. This remark also needs to be considered when considering the design criteria of the ScenarioMIP pathways. These design criteria depended to a large degree on global mean temperature anomalies.

In Chapter 4, we review existing scenarios. For this purpose, we use the AR6 database that has been published along with the WG3 contribution for the Sixth Assessment Report of the IPCC. We added more recent scenarios from projects that started after AR6 (ENGAGE version 2.0, NAVIGATE, SHAPE, NGFS version 4.2). Moreover, we filter the database to exclude scenarios that do not fit vetting criteria when comparing scenarios with historical data (Guivarch et al. 2022). We call this database AR6+.

1.3 ScenarioMIP and previous scenario exercises

The preparation of the IPCC Assessment Reports (ARs) sets important orientation points for the scientific processes that contribute to the ARs. Thus, the scientific cycles and the IPCC AR cycles work in tandem. The ongoing CMIP7 cycle is supposed to deliver crucial information for the IPCC's Seventh Assessment cycle.

ScenarioMIP is part of CMIP (Coupled Model Intercomparison Project) that is headed by the World Climate Research Program of the World Meteorological Association, the International Council for Science and the UNESCO. ScenarioMIP is of particular importance for the CMIP, but is formally organized similarly like multiple model sub-projects within CMIP. ScenarioMIP is supposed to provide anthropogenic forcers of the global climate system which are evaluated by climate models.

The CMIP6 cycle that contributed to the Sixth Assessment cycle of the IPCC used a subset of the Shared Socioeconomic Pathways (SSPs) that have been developed by the Scientific Working Group on Scenarios by the Integrated Assessment Modelling Consortium (IAMC). The SSPs are scenarios that were first developed by Integrated Assessment Modeling (IAM) teams (Riahi et al., 2017), then prepared as inputs for the climate models (Gidden et al., 2019; Hurtt et al., 2020; Meinshausen et al., 2020). The subset of scenarios of scenarios from the SSPs used by ScenarioMIP in CMIP6 is documented (O'Neill et al., 2016). Although the SSPs were not primarily developed for the ScenarioMIP process, but as general projections for many different research topics and communities. Still, the most prominent application was the use for evaluating future climate change in CMIP6.

1.4 ScenarioMIP and the Seventh IPCC Assessment Cycle

Figure 3 provides an overview of the ongoing ScenarioMIP exercise and the relationship of the IAM with the ESM and IAV communities. The triangular structure is a true novelty. In previous assessment cycles the structure followed a linear cause-effect approach (see Pirani et al. 2024, Figure 1, "Data Flow"). The IAMs delivered only climate forcers to the ESMs, which were run in concentration driven mode; thus, not fully accounting for the climate-carbon cycle feedbacks. This process tended to take so much time that the IAV community needed to rely on climate outcomes from the previous assessment cycle. Thus, the cause-effect chain was informed by a set of scenarios that lacked consistency as model versions were not from the same vintage (Pirani et al., 2024). So far, the DHFs have not been fully considered within ISIMIP due to the lack of integration and coordination between the working groups.

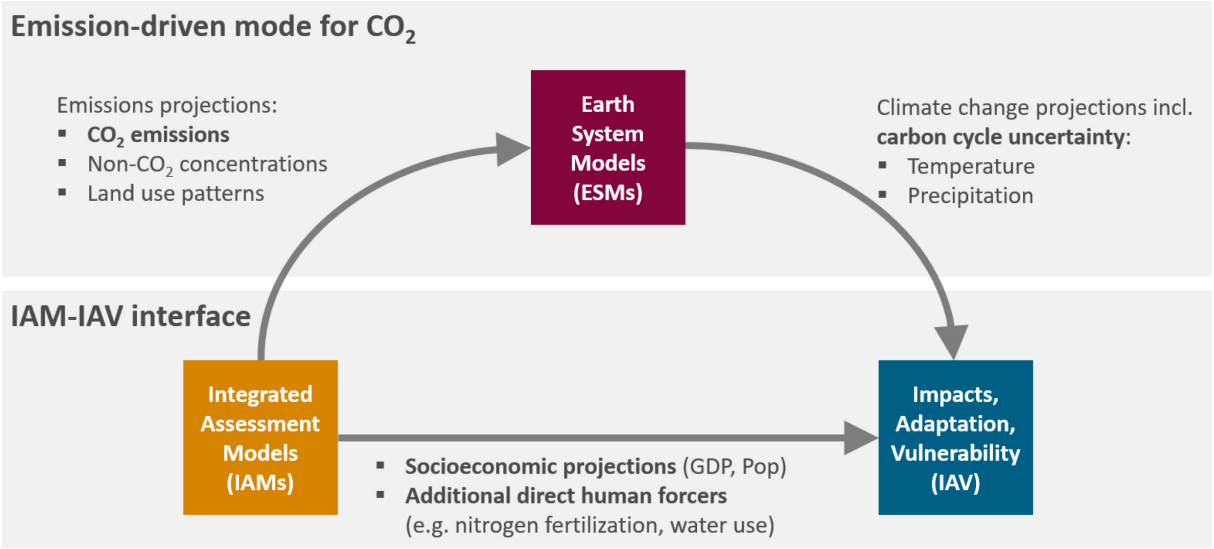
The major novelties for the ScenarioMIP within CMIP7 will be that Earth System Models will be used in emissions-driven mode for CO_2, which implies that all emissions and land-use results from the Integrated Assessment Models will be used directly in order to get a full picture of the uncertainties incl. feedbacks from the climate system to the carbon cycle (Sanderson et al. 2023). Emission-driven mode is important for an appropriate understanding of the dynamics and risks of overshoot scenarios. Moreover, it is planned to feed the Impact Models with the outputs of the Earth System Models (Jones et al. 2024). As mentioned above, the difference is that in previous assessment cycles, IAV models were fed with results of climate models from the previous Assessment cycle. Thus, the framework mixed information of different generations of modeling tools and generations of scenario. Finally, it is envisaged to feed the Impact Models not only with the results from the Earth System Models, but also to use the Direct Human Forcers derived from the same scenarios of the Integrated Assessment Models (Frieler et al. 2024). Each of these novelties is a major improvement compared with previous assessment cycles. The ambition is

even higher because the time span for accomplishing this difficult task has been shortened from seven to five years (Pirani et al. 2024)

The ScenarioMIP process and concept has been discussed in the international scientific community and coordinated in CMIP. The shortening of the duration of the Seventh Assessment cycle has increased the ambition for the scientific communities to better coordinate and integrate the overall process. Nonetheless, a substantial amount of the planned processes and research efforts is not yet funded, particularly the IAM-to-IAV interface in Figure 3. The main reason is that ScenarioMIP in the narrow sense only comprises the link from IAMs to ESMs. Although the full integration is the overall ambition it has not been appropriately appreciated in research strategies.

Figure 3: Overview of the broader ScenarioMIP process

The figure shows the three scientific communities (ESMs, IAMs, and IAV) related to the three IPCC working groups and the data exchange discussed in the ScenarioMIP paper by van Vuuren et al (2025).



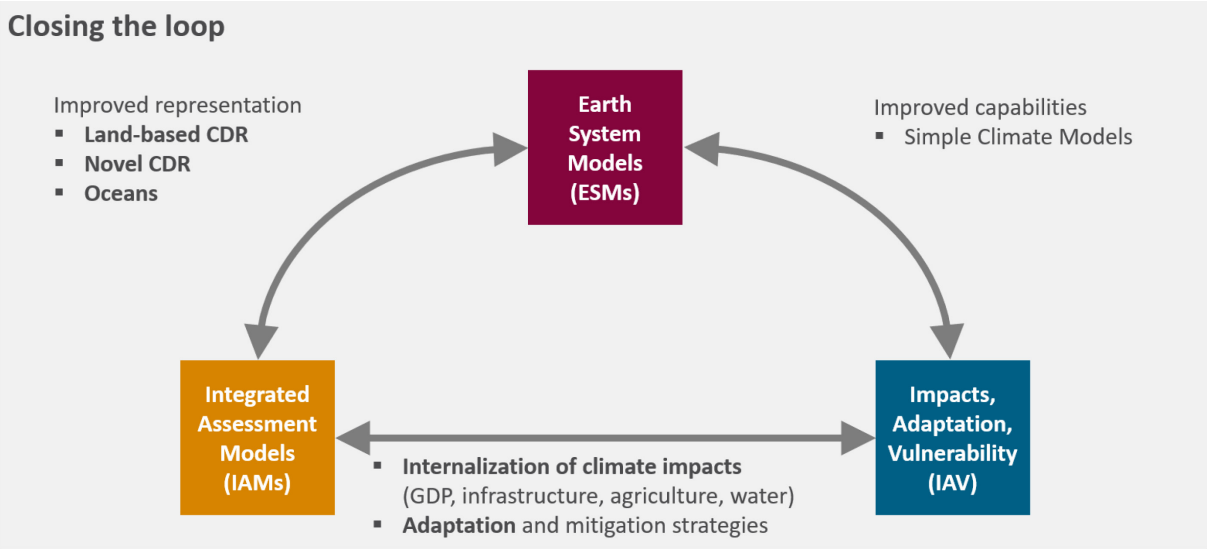
Source: own compilation.

To inform policies, it is not enough to feed the information through the IAM-ESM-IAV chain of models because this would only result in the quantification of the negative effects of climate change. The next level is to close the information loop and feed the information back into the IAM models so that the behaviour of actors is changed (see

). This requires the integration of the information flow in an efficient way. ESMs and Impact Models are computationally too heavy to be integrated in full into a single computational framework. Therefore, reduced form models of ESMs and Impact Models (so called climate emulators and impact emulators) can be formulated and integrated into IAMs. In this context, also the inequality of affected households and social groups can be represented and valued for the policy response. The full integration of the impacts is also useful to derive the financial consequences of the impacts and adaptation mechanisms. This would be applications of IAMs that are useful for WG2 of the IPCC as well as the Synthesis report.

Figure 4: Overview on future research based on ScenarioMIP process

The figure shows the three scientific communities (ESMs, IAMs, and IAV) related to the three IPCC working groups and the future data exchange beyond the ScenarioMIP paper by van Vuuren et al (2025).



Source: own compilation.

1.5 ScenarioMIP and Paris Process of NDCs and GSTs

The final document of the First Global Stocktake[6] (GST-1) adopted in 2023 in Dubai, United Arab Emirates, highlighted the important role of the IPCC to inform the GST (#14), particularly the modelled global pathways and general guidance that this information provided (#26). GST-1 invited the IPCC to contribute timely information to the second and all following GSTs (#186). ScenarioMIP as part of CMIP contributes crucial scientific inputs that the IPCC can use in the up-coming Seventh Assessment Report (AR7). The exact information demand has not been formulated in the GST document.

The ScenarioMIP process aims to generate information for the Second Global Stocktake (GST-2) that is scheduled for 2028.

First, the scenarios of ScenarioMIP provide the informational basis for updating climate change projections and the resulting impacts in various sectors. The scenarios will provide information about the lowest level of climate change that can be achieved as well as the upper end of climate change that policy makers have to expect and prepare for. The previous round of ScenarioMIP that informed AR6 relied on scenarios of the SSPs that are outdated by now and will be irrelevant by 2028.

Second, the ScenarioMIP results will not be relevant for the COP in Belem and the negotiations of the NDCs for the years 2035 and beyond, but scenarios will set a new benchmark against which the NDCs and the progress of National Policies will be compared.

Third, the new set of scenarios will provide new pathways for future temperature developments. The lowest scenario will – with very high likelihood – not be compatible with the C1 category of the AR6 of the IPCC because emission reductions over the past years were not sufficient. This is important because GST-1 has chosen this class of scenarios as the benchmark (GST-1, #27) against which global transformation targets for the energy, industry and land-use sectors were matched (e.g. GSP-1, #28). Such approach could also be followed in GST-2. In this case, a new

[6] Document number FCCC/PA/CMA/2023/L.17 to be found: https://unfccc.int/sites/default/files/resource/cma2023_L17E.pdf

benchmark scenario needs to be chosen. ScenarioMIP offers a set of scenarios that allows such a choice. Such scenario would also establish the benchmark against which the NDCs and National Policies as implemented (NPis) are compared. Therefore, we present not only the emissions and land-use data, but also – to some degree – the underlying transformations. For instance, the new ScenarioMIP specifications ask for one scenario that explores how deep and how quick GHG emissions could be reduced without threatening sustainability criteria by excessive CDR deployment.

2 Overview on Integrated Assessment Models and Policy Analysis

Integrated Assessment Models (IAMs) denote a broad set of models developed for scientific purposes and to inform the public and policy makers about policies related to climate, energy, land use and other topics. The variety of modeling approaches and scenarios offer a broad spectrum of perspectives on policy choices. We provide an overview of the different model types and the policy analysis approaches that can be applied. We give an overview about policy instruments that can be implemented and analyzed with the different modeling approaches. We separate both topics because policy instruments do not necessarily match in a one-to-one way with modeling approaches nor with policy analysis modes. This means the same policy instrument can be analyzed with different modeling approaches and in different policy analysis modes. Moreover, it should be noted that IAMs were developed over many years and often combine different modeling approaches and can also analyze policy mixes with various instruments. Therefore, conceptual categories are often difficult to apply on IAMs because various modeling approaches are combined and the analysis of policy mixes becomes increasingly more important.

This overview also provides a reference point for the discussion of the implementation of scenarios in ScenarioMIP, knowledge gaps, and the strategic research recommendations that are detailed in this report.

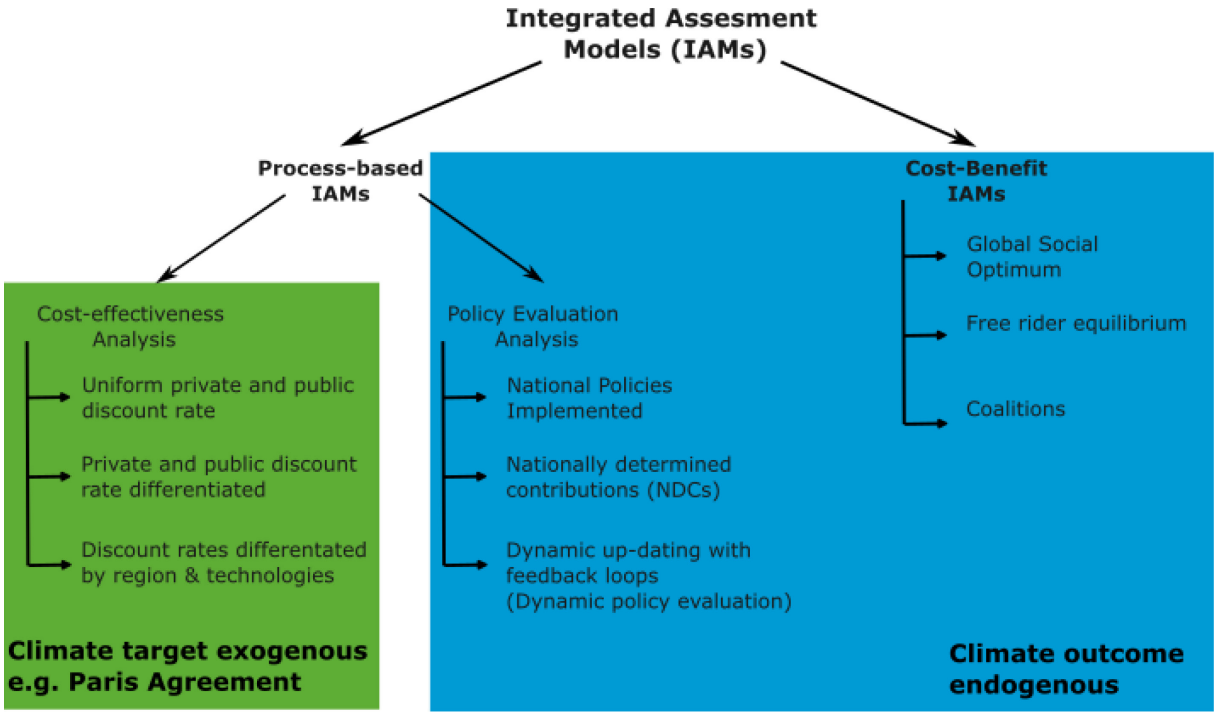
2.1 Process-based and cost-benefit IAMs and policy analysis

Figure 5 shows the overview of modeling tools. Weyant (2017) introduced a canonical classification of IAMs distinguishing process-based and cost-benefit analysis IAMs. The distinction is to a large degree pragmatic rather than guided by purely conceptual differences. There are overlaps regarding methods and approaches and further model developments might make the distinction gradually more obsolete over time. A major difference is that process-based IAMs are more detailed with respect to emissions, land-use change, their socioeconomic drivers and the underlying technological transformations. Cost-Benefit Analysis IAMs are simpler in this regard, but close the informational loop to include damages and impacts caused by climate change that feed back into the socioeconomic system and potentially induce policies in an interactive manner. Cost-Benefit-Analysis IAMs close the loop of the information flow in both directions. First, they include the effect of emissions on the climate system and the impacts on the socio-economic system. In environmental economics this is an environmental externality. Second, the externality is internalized by a policy instrument (see also Section 2.2) that endogenously relates its strength to the impacts (externality). The most common approach is to impose a Pigou tax (internalization) that equals the cost of pollution (externality). Due to the complex system interactions, the models of the different components are relatively simple and use highly reduced and stylized emulators.

Process-based IAMs, such as REMIND-MAgPIE, are used to derive mitigation scenarios and serve as a methodological approach to derive future climate forcer data inputs for Earth System Models (ESMs) and are a major basis for the IPCC assessments of mitigation potentials in WG3. Different to the Cost-Benefit IAMs, process based IAMs in most cases do not explicitly relate the policy (internalization) to the adverse effect of climate change (externality). Alternatively, process based IAMs rely on user defined assumptions about the strength of policies and targets (see below for more details). This reduction in the level of integration allows much more detailed representation of multiple interacting systems. The integration of damages and the

corresponding internalization of the climate externality is ongoing research (Schultes et al., 2021).

Figure 5: Overview on IAMs and policy analysis modes



Source: Own compilation.

The notion of the process-based modeling approach refers to the explicit representation of choices and activities that are related to energy conversion, production activities as well as land-use changes. The process-based bottom-up models of specific sectors can be combined with a top-down model to also represent the broader context of population and macroeconomic income within which savings, investment, trade and international finance, energy and agriculture are embedded and interact in multiple ways. For instance, the production of goods and services measured by GDP demands energy that is supplied by the energy sector, which in turn demands economic resources that are accounted for in the macroeconomic balances for the use of GDP (Bauer et al. 2008). Such combination of bottom-up and top-down modeling is commonly classified as hybrid models; REMIND-MAgPIE belongs to this model category.

The explicit representation of processes and activities allows for a great flexibility to extend the modeling tools to represent multiple variables relevant for climate, the environment, and socio-technical system transitions. For example, the production of electricity by coal power plants is associated to CO_2 emissions from combustion as well as other air pollutants such as Sulphur Dioxide (SO_2). Combining this with information about socioeconomic changes from the top-down economic model, such as impacts on income and energy prices, helps to derive a broad set of indicators that are relevant for evaluating the impacts on Sustainable Development Goals (SDGs). The coupling of activities to variables that represent emissions and other SDG-relevant issues can be flexibly added (this is discussed in more detail in Section 4.8). Moreover, the explicit representation of investment processes connects physical conversion activities with economic relevant systems such as the financial system and international trade (this is also discussed in Section 4.4). This modeling approach renders the systematic analysis of integrated systems and sectors possible and allows to identify multiple trade-offs and synergies within and across sectors.

Process-based IAMs can be run under different assumptions to analyze climate policies. For assessing long-term mitigation strategies, the IPCC mostly reviews scenarios run as cost-effectiveness analysis (CEA). In CEA scenarios, an exogenous constraint for global climate change protection is set. The target level can be informed by a broader analysis and assessment of climate impacts and considerations about risk and the precautionary principle. The model is then run to respect the limitations set by the constraint at the lowest cost to society. Thus, the target is effectively achieved in a cost-minimal manner, given the climate objective and all other constraints considered in the model and the scenario set-up. The climate objective can be implemented by a constraint, for example, to limit cumulative CO_2 emissions below a carbon budget and it can do so with or without temporary overshoot. In the CEA mode, the discount rate for public policy choices has a strong influence on the time path of emissions that is consistent with the long-term target. Generally, higher discount rates imply a steeper growth of the CO_2 price. However, it does not affect the long-term target, which is set exogenously, e.g. the cumulative emissions up until 2100. Therefore, a higher discount rate implies less mitigation in the near term and a delay of policies towards later periods. An important assumption is that the long-term objective is achieved over the time horizon. Thus, the intertemporal allocation assumes an effective enforcement mechanism. A more detailed discussion about the time path of the CO_2 price follows in Section 4.2.

Alternatively, most short-term analysis applies the policy evaluation analysis approach, in which a set of explicit near-term policies is imposed and the implications for the GHG emissions and other indicators, such as policy costs, are derived. These policies can address emissions or any other variable that is represented in the model structure. This can include renewable capacity targets, energy efficiency targets or nature-oriented land-protection measures. The near-term policies can, for example, cover the national policies implemented as of today, or the announced NDC targets, or any other policy package under consideration. In the policy evaluation mode emissions are fully endogenous and are not necessarily consistent with an exogenous long-term climate target.

The IPCC uses scenarios that follow either the policy optimization and the policy evaluation approach or also combinations to gain insights into the relationship between near-term policies and long-term targets. For example, the emission gap highlighted in the SPM of IPCC AR6 WG3 is derived by comparing the emissions of a cost-effective scenarios with the emissions achieved by implementing, for example, the NDCs. For this comparison the choice of the cost-effective scenario is crucial. The ScenarioMIP scenarios provide a first set of scenarios from which this benchmark scenario can be chosen.

Climate change is a policy issue that touches on private investments and public policies over long-time horizons. For the long-term CEA, an important question concerns the assumptions about discounting, which is highly relevant for the valuation of policies and investment choices. In this context, it is useful to basically distinguish the private and the public discounting. The public discounting affects the policy choices over time and therefore the pathway of emissions consistent with the long-term target. Differently, the private discounting relates to the private investment decisions and has strong influence on the cost structure of alternative production modes, such as the capital cost component of the levelized cost of electricity production. In most IAM scenarios, the private and public discounting are not explicitly differentiated but assumed uniform. Moreover, it is worth to note that it is possible to differentiate private discounting across regions to reflect imperfections in capital markets and represent risks. Similarly, it is possible to differentiate the public discounting across regions to reflect heterogeneity in public choices. Besides conceptual and theoretical issues, the empirical basis for justifying concrete assumptions about the differentiations is weak and only slowly developing.

As mentioned above, in most cases process-based IAMs do not include feedbacks of climate change on economic development. The analysis of such feedbacks is usually performed with so-called cost-benefit IAMs such as DICE, FUND, PAGE, etc. These models can be used to derive socially optimal global warming levels by choosing emission pathways that balance the inter-temporal trade-off between near-term costs of emission reductions with the beneficial effect of avoiding negative consequences, such as GDP losses, that would be caused by unabated climate change. In this trade-off structure, emission reductions can be interpreted as an investment that improves environmental quality in future periods as compared with a no-policy case. Thus, the assumptions about discounting play an important role for the cumulative emissions and the level of global warming that are endogenously derived and not exogenously assumed as in the CEA. In Cost-Benefit Analysis the assumptions about damage costs from unabated climate change are highly uncertain and have a strong influence on the results (e.g. Moore and Diaz 2015, Burke et al. 2015), the assumptions about discounting have substantial influence on the long-term warming level and the strength of near-term emission reductions. The main effect is that higher discounting lowers the value of future damages caused by emissions today and therefore less emission reductions are derived. This can be explained by the relationship to the Social Cost of Carbon (SCC) that inform the justification of a tax level on emissions. The SCC measures present value of all additional damages in the future caused by an additional ton of CO_2 emitted into the atmosphere. The time path of these additional damages is discounted to derive the SCC and a higher discount rate leads to a lower SCC and thus implies lower emission reductions and higher long-term warming level.

The assumption about the discount rate in cost-effectiveness analysis is subject to long-standing and heated debates. A major dichotomy in the debate is whether the public discount rate should be based on ethical principles of inter-generational justice or empirical studies that are based on saving decisions of private households (for literature, see Stern 2008). More recently, a compromise has been proposed to value low and high values with equal probability weights and derive the expected equivalent discount. This leads to relatively high near-term discounting that slows down over time and approaches the lower discounting (Arrow et al. 2013). Another alternative is to apply different discount rates in a transparent way and leave it to policy makers to decide about the choice, arguing that research can map out the consequences of alternative choices, but cannot decide about it. For the different choices of discount rates, the resulting SCC and warming levels differ greatly as has been shown in the literature (Nordhaus 2017, Anthoff et al. 2009).

The CEA mode circumvents the dispute about the optimal warming level (and the potential influence of the discount rate) by setting the long-term warming target exogenously. This neutralizes the corresponding uncertainty. In both cases, the CEA and the CBA analysis, a lower discount rate implies stronger near-term mitigation. The other arguments about discounting mentioned above are still valid for the CEA analysis.

Another important question for CBA-IAMs in the context of multi-regional model analysis concerns the aggregation of damages across regions. The globally optimal climate policy aggregates damages across all regions, which represents the largest degree of international policy integration within the corresponding model context; the resulting optimal carbon tax in all regions would equal the global SCC. At the opposite end of the spectrum is the free-rider equilibrium in which all regions only consider their domestic damages, but ignore damages in other regions and countries. This is also known as the outcome of the prisoner's dilemma with social negative consequences of pollution or – more technically – the non-cooperative Nash equilibrium without permit markets. Consequently, each country only implements carbon pricing up to the level justified by their domestic climate damages. Such free-rider equilibrium is

not socially optimal and global warming would be substantially higher than the socially optimal level. It is the theoretically implied result, if no policy coordination is achieved. The consideration of only national cost of carbon has been proposed by the first Trump administration (2017-21), along with a discount rate of 7%/yr. Consequently, the SCC derived was negligible.

In between these two ends of the spectrum various intermediate solutions could be derived that fit different criteria. A notable literature has developed in the field of endogenous coalition formation. Basically, the IAM is run multiple times with variations of coalitions of countries that form aggregate regions and coordinate policy. By simple comparison, stable coalitions can be identified in which countries would not change their choice of leaving or joining a coalition for economic reasons. By adding additional policies, such as transfers or the imposition of tariffs against outsiders, coalitions change and can induce greater levels of global emission reductions. Another strand of literature has been developed around the concept of Lindahl solutions for the provision of public goods. In this approach, countries can interact by contracts in which one country contributes transfers to the emission reductions in another country. This approach is mainly based on the willingness to pay for emission reductions. Such mechanism opens the possibility that countries with high climate damage costs can buy additional mitigation efforts from countries with high emission reduction potentials, but low damages. Under standard assumptions applied in economic theory (full information, no transaction costs, atomistic actors without strategic market power) such decentral negotiation scheme has the potential to get close to the global social optimum. In the real world such set of bilateral agreement would be excessively complicated and the likelihood is high that institutional issues become relevant as constraining factors, such as double counting. Despite its theoretical appeal, this approach has not been widely implemented in IAMs due to technical and numerical difficulties (for an exception see Groot and Swart, 2018).

The exclusion of climate damages that feed back into the dynamics of economic development in the top-down macroeconomic part of hybrid IAMs has been called into question, since Burke et al. (2015) estimated substantial impacts of global warming on economic activity, i.e. GDP. Recent estimates are substantially higher than those in earlier research, especially those used in the FUND and the early versions of the DICE model. Also, the inclusion of climate feedbacks on the agricultural, fishery and forestry sector as well as the energy demand and energy supply by representing the process-based impacts in a bottom-up manner is prospective research. Both routes of research would imply that emissions and land-use would react endogenously in a feedback loop with the climate system.

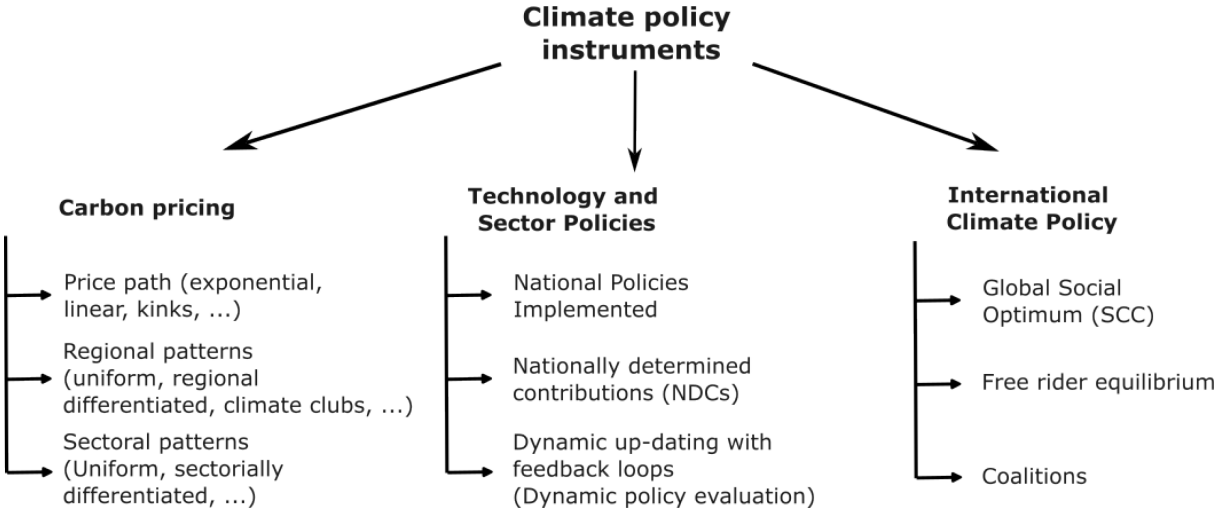
2.2 Analysis of policies and policy instruments in IAMs

IAMs can be used to assess policy instruments (see Figure 6). The analysis mode of IAM policy scenarios does not necessarily coincide with the choice of policy instruments. This independence of policy mode and policy instrument choice is a particularly important remark to avoid confusion.

For instance, the REMIND and the MAgPIE models compute economic equilibrium by combining optimization methods and iterative fixed-point methods. For a given climate target, such as a carbon budget that constrains global cumulative emissions, the coupled model framework derives the optimal strategy given the socioeconomic, technological, political and geobiophysical constraints. This optimal strategy is a portfolio of mitigation measures that consider, among others, the investments and operations of energy technologies and the use of energy as well as land-use change and management and yield increases. The individual choices of the mitigation portfolio share the characteristic that the emission abatement level is increased to a degree

where they are at or below a common level. One approach to implement this emission limitation strategy is the imposition of technology and sector policies, such as feed-in tariffs and energy efficiency standards. The set of policies needs to be comprehensive and well-balanced across sectors and technologies. The emission reductions would follow indirectly from the transformation of sectors and technologies. Alternatively, this solution could be implemented by an emission taxing system that covers the sectors, gases and regions as required in the optimal solution. The transformation of technologies and sectors would follow indirectly from the policies targeting emissions. The equivalence of both solutions is a property of the optimality condition that precluded economic actors from undertaking activities that lead to economic losses.

Figure 6: Overview on policy instruments that can be analyzed with IAMs



Source: Own compilation.

Therefore, carbon prices that are derived with IAMs are frequently used as indicators for the level of policy ambition, but it is not necessary that the mitigation strategy is implemented by means of carbon pricing policies. Even if carbon pricing policies are not chosen as a policy instrument in the real world to implement the mitigation strategy, the indicator from the modeling exercises is still useful because it makes scenario results comparable across sectors, regions and even models and it gives valuable insights about the time path of the stringency of policies.

The concept of carbon pricing has been criticized by social and political scientists. A recent review of arguments and their validity is provided by van den Bergh and Botzen (2024). A general challenge for both approaches is the comprehensive coverage. While sector and technology policies may not address all mitigation measures such as specific efficiency measures and sector coupling by end-use electrification based on renewable electricity, emission pricing systems must not allow loop-holes like exempting industry sectors.

Also, the Social Cost of Carbon (SCC) derived with CBA-IAMs do not necessarily imply that carbon pricing policies are implemented. For instance, the US regulations implemented under the clean air act have been justified by the SCC. The Interagency Working Group assessed the SCC using three different Cost-Benefit IAMs.[7] Individual policies to reduce emissions were tested against these SCC. If the cost of mitigation per ton of CO_2 were below the SCC the policy justified under the clean air act and was, thus, justified for real world implementation. This allowed the

[7] For example https://www.epa.gov/sites/default/files/2016-12/documents/sc_co2_tsd_august_2016.pdf

US Environmental Protection Agency to introduce regulations to lower CO_2 emissions under the Clean Air Act without any need for additional legislation. This approach was chosen due to the expectation that a specific carbon pricing policy like an explicit taxation of CO_2 emissions would have failed the US-congress in the legislative process.

Another important issue is that policy ambitions across regions and sectors can vary widely. These very different levels of policy strength can be analyzed by means of carbon prices differentiated by region and sector. The differentiation across regions can help to investigate the principle of *Common-but-differentiated-responsibilities-and-respective-capabilities* (CBDR-RC). The differentiation across sectors and/or regions can help to understand the effects of incomplete coverage of emission sources and the corresponding leakage effects. Again, the resulting effects are not necessarily features of the carbon pricing instrument, but are the result of differential treatments of sector and regions that would also result from technology and sector policies, if they treat different emissions sources from sector or regions differently.

3 Overview on the ScenarioMIP design

The selection of the six scenarios in the ScenarioMIP framework is built on two key principles. First, the selected scenarios should cover a wide and plausible range of future emissions and land use outcomes. Second, the scenarios are meant to be illustrative for different future developments, which is especially important given the limited number of scenarios that can be included in ScenarioMIP due to computational costs of ESMs and limitations to analyze results.

Following (van Vuuren et al., 2025, in review), we describe the qualitative scenario narratives and the main research questions addressed by these scenarios. Based on further, intensive exchanges in the Integrated Assessment Modelling Community, we also provide additional specifications of the scenarios that form the basis for a consistent implementation by the Integrated Assessment Models and are important for multi-model comparisons.

In view of the overall ScenarioMIP timeline and ScenarioMIP's objective to provide a key input to the IPCC AR7 and the Second Global Stocktake (GST) in 2028, the scenarios are designed to show only small variations in the near-term so that they can be expected to still represent plausible scenarios when used and discussed in 2028 to 2030. Therefore, all scenarios are identical and fixed to current trends and policies in 2025, and remain within a relatively narrow range until 2030.

3.1 High emission scenario

The High Emission (H) scenario outlines a plausible future in which global climate policies weaken or collapse altogether, and efforts to mitigate greenhouse gas emissions largely fail. It envisions a world where political will to address climate change diminishes, international cooperation breaks down, and nations increasingly prioritize economic growth and national security over environmental concerns. As a result, fossil fuel use remains dominant, bolstered by concerns about jobs and competitiveness.

In this scenario, public support for climate action declines, there is significant resistance to the energy transition, and the rapid progress in renewable energy witnessed over the past decade slows. Industries and societies adopt more energy- and resource-intensive modes of production and consumption, barriers to the deployment of low-carbon technologies persist, and fossil fuel industries maintain strong influence.

The scenario is designed to explore the high end of plausible future greenhouse gas emissions and the resulting potential high-end impacts. This scenario helps examine the risks of high warming levels, including tipping points in the climate system and the limits of adaptation.

3.2 Medium emission scenario

The Medium emission (M) scenario serves as a benchmark scenario by assuming the continuation of current policies and current trends over the century, but with no additional action being taken. The scenario only considers implemented policies and does not take policy targets into account which are not yet backed by corresponding legislation; i.e. NDCs or net-zero pledges are not included. In particular, it does not include any progress in mitigation policies after 2050. While climate policy efforts are frozen in this scenario, variations of socio-economic and technology assumptions should be explored to quantify the uncertainty range of temperature outcomes under current policies.

3.3 Medium-Low emission scenario

The Medium-Low emission (ML) scenario assumes the continuation of current policies and current trends until 2040 as reflected by the M scenario. After 2040, climate policy ambition increases moderately. Although, the scenario reaches net-zero CO_2 emissions around end of the century, efforts are insufficient to meet the targets of the Paris Agreement.

3.4 Low emission scenario

The Low emission (L) scenario addresses the question how the 2°C target can be safeguarded, and its temperature outcomes are thus required to stay below 2°C with at 67% chance at all times (C3 category of the IPCC AR6). It is one of three scenarios that are anchored in the temperature targets of the Paris Agreement. As explained in Section 1.2, the temperature outcomes presented in this report are preliminary given the nature of the ScenarioMIP process.

In 2030, GHG emissions reflect the NDCs (for 2030) provided these are still plausible to achieve. Thereafter, emissions decrease to reach net-zero CO_2 emissions around 2070 and net-zero GHG emissions around 2100.

3.5 Very Low with Limited Overshoot

The Very Low with Limited Overshoot (VLLO) scenario explores the lower end of plausible future GHG emissions and temperature outcomes. It aims to keep peak warming and the duration of a temporary overshoot of 1.5°C "as low as plausible". The scenario is centred around sustainable development and takes Sustainable Development Goals (SDGs) beyond Climate Action into account.

In 2030, the scenario balances current trends and policies with current pledges as represented, among others, by the NDCs, and feasibility limits. As outlined at the beginning of this section, it is important that the VLLO scenario is still plausible when used in 2028 to 2030. After 2030, CO_2 emissions and other GHG emissions are reduced as rapidly and deeply as plausible to limit peak warming.

These reductions are enabled by a fast decarbonization of electricity supply, a deep electrification of energy demand sectors, and behavioural changes in transportation, consumption and diets. The VLLO scenario implements sustainable land futures, enabling to reach net-zero GHG emissions while keeping the carbon dioxide removal limited.

3.6 Very Low after High Overshoot

The Very Low after High Overshoot (VLHO) scenario features a higher overshoot of the 1.5°C temperature target compared with the VLLO scenario (see below), which is is the consequence of delayed emission reductions. It analyses the impacts of a higher overshoot, the costs and trade-offs of a large deployment of carbon dioxide removal, and it enables to study the costs of a longer and higher overshoot of 1.5°C compared to the VLLO scenario.

Until 2030, the VLHO scenario follows current trends and policies as reflected by the M scenario. In 2035, climate policy ambition remains relatively weak (compared to the VLLO and L scenarios). Thereafter, it features deep emission reductions and reaches net-zero GHG emissions globally around 2070. A clear separation of the VLLO and VLHO scenarios in terms of peak warming is an important design criterium, and to this end, the respective peaks of the cumulative CO_2 emissions should differ by 400 to 600 Gt CO_2.

In the second half of the century, the deployment of carbon dioxide removals is rapidly scaled up within feasibility limits to reach amounts of net-negative emissions that are at the upper end of the plausible range. Thereby, the VLHO scenarios aims at decreasing temperature to 1.5°C as quickly as plausibly possible. The resulting temperature outcomes by the end of the century and whether similar temperature levels as in the VLLO scenario can be achieved after a high overshoot, are key research questions addressed by ScenarioMIP.

4 Literature Review and Knowledge Gaps

In this chapter, we review the literature and identify knowledge gaps in each section. This prepares the derivation of the strategic research needs that will be highlighted in the concluding Chapter 7. A matching of the knowledge gaps with the ScenarioMIP scenarios is provided in Section 4.13.

4.1 ScenarioMIP and the NDC-GST cycle

The major difference between the Kyoto protocol and the Paris Agreement is that in the Kyoto protocol only developed countries and countries with economies in transition committed to emission targets and time tables, whereas the Paris Agreement all countries committed to a permanent process of ratcheting up national policies with the global objective to limit global mean temperature increase to 1.5°C.[8] The process consists of five-year cycles with new national commitments and a review combined with global strategies. The COP in 2023 in the United Arab Emirates concluded the First Global Stocktake (GST-1) that identified key areas for increasing the ambition level for the next round of NDCs that will be negotiated at COP30 in 2025 in Brazil. The NDCs need to be substantiated by concrete national policies, that will be reviewed at COP33 in 2028, which is supposed to finish the Second Global Stocktake (GST-2).

Given the time schedules of the negotiation process and the scientific assessment process, the applicability of the ScenarioMIP scenarios requires some qualification about their purpose and intended applicability as well as assessment of the requirements for a proper investigation of a new round of NDCs and National Policies as implemented (NPi) and the GST.

The specifications in the ScenarioMIP protocol require the modeling teams to submit scenarios that consider NPis up until 2025. Thus, in this very year, scenarios submitted by each modeling team are required to feature equal emission levels; this does not imply that all modeling teams will feature equal emissions in 2025 given the model specific calibration routines.[9] For the year 2030, the scenario specifications vary (see Chapter 3), but are subject to constraints implemented by the modeling teams. For the specifications of scenarios consistent with different interpretations of the long-term target of the Paris Agreement, the criteria range from the consideration of National Policies implemented to model specific flexibility in 2030. These are crucial parameters for applying the scenarios for the evaluation of the new round of NDCs and the subsequent implementation of policies.

For policy analysis in the future, the new scenarios from ScenarioMIP can be used as benchmark to derive the ambition gap between these scenarios and the updated NDCs after the COP in Brazil in 2025. This exercise has been performed in the past to inform the policy process (e.g. Kriegler et al 2015, Riahi et al. 2015, Fawcett et al. 2015, Roelfsema et al. 2020, Iyer et al. 2022), which have been acknowledged in the Paris Agreement as well as in GST-1. Also, the UNEP gap report relies on this information derived with IAMs. This emission gap identifies the difference between the policy ambition in, e.g., 2035 or 2040 and the emissions permissible to comply with the Paris Agreement in a cost-effective manner. For the negotiations expected at COP30 the feasible global emission reductions are a key information to argue for more ambitious NDCs. The greater the near-term flexibility for emission reductions the more ambitious is the benchmark for the comparison with the new NDCs. Depending on the assumptions about near-term

[8] Article 2 of the Paris Agreement states: "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change."

[9] In a separate step it is planned that a subset of scenarios from all teams, the so-called marker scenarios, will be harmonized to historic data. The expected year for data harmonization is 2023. The harmonization step is technically, not with the IAM teams.

feasibility the ambition gap changes accordingly. Fixing the 2030 emissions to old NDC or even NPi would make the comparison with the updated NDCs and NPI less useful because this comparison assumes only very little near term flexibility. However, changes to these assumptions can be made to provide the information basis for a timely assessment of updated NDCs and NPi. A crucial point is that the benchmark scenario against which the NDCs are compared needs to be chosen. The set of alternatives is to some degree set by the ScenarioMIP specifications because these scenarios provide a crucial framework for future research. For the GST-2, it is important which scenario classes the IPCC will agree on for the benchmarking (see e.g. GST-1, #26).

Once the NDCs are decided at COP30, the focus is expected to move towards the implementation gap. This is the difference between the implemented policies and the NDCs. This will be a rolling process as implemented policies will be updated as it is intended by the process of the Paris Agreement. IAMs are important tools to inform the process at the various stages of the five-year cycle. Thus, in preparation and in the aftermath of the COP30 in Brazil, more publications are expected that assess the required emission reductions and the comparison with the proposed NDCs.

The timely availability of information on the emission and implementation gap requires continued updates of the NDCs and the policies implemented and also policies that are debated. The computation and analysis of results requires continued effort to build and maintain stable and efficient compilation, interpretation, processing and analysis of scenarios and comparison with real-world data. The PIK team is often contacted by national modelling teams to assist and advice on modeling. A lack of resources makes stable collaboration more than challenging.

Another issue that must be mentioned in this context is the consideration of the long-term strategies (LTS) that mostly consider the achievement of net-zero targets (be it GHG or carbon neutrality). The interaction and consistency between the near- and mid-term targets, the international trade and carbon leakage effects as well as the synergies and trade-offs between these targets are not explored as of today. This is a promising field of future research to identify the most crucial regions and sectors for additional policies and international cooperation. The analysis of an international steel sector policy could be an example.

Progress in research and scientific advances can be achieved by endogenizing political dynamics and the interaction with technological changes and socioeconomic systems. By doing so, it could be tested what the expected effects of policy initiatives (unilateral or in collaboration with partners) are. This general approach, termed dynamic policy evaluation is a logical development of the policy evaluation mode discussed in Chapter 2 and has been recently published for the case of coal phase-out (Bi et al., 2023). The scientific approach has been highly appreciated in the scientific community (Gambhir, 2023).

Moreover, the new ScenarioMIP scenarios can serve as a guide for the GST for up-dating the transformation targets, such as tripling renewable energy capacities or slowing of deforestation, that are supposed to facilitate the increasing ambitions of future NDCs (GST-1 #27). The IAM runs derive the emissions and land-use scenarios as results from transformation processes that are represented in detail at the regional, sectorial and technological level. Therefore, the IAM scenarios can serve as tools to connect emission targets to transformation targets that will require an update at the GST-2.

Since climate policies have been proposed and implemented for many years, it is also possible to compare past pledges, such as those of Copenhagen in 2009, with realized emissions in 2020 (Li et al. 2024).

4.2 Carbon price over time and overshoot

Temporary overshooting of a long-term climate target has been and still is intensively discussed. An implicit assumption in the discussion has been that the long-term temperature after an eventual overshoot is higher than today's temperature. Thus, the implicit assumption always was that the overall overshoot to exceed the target by a certain magnitude and duration is entirely in the future. This means that the long-term temperature is still higher than the temperature today; in both cases with or without overshoot. Very low emission scenarios can lead to long-term temperatures that are below today's temperature. Please note that the long-term target needs not to be the 1.5°C but could be even lower even if the overshoot exceeds the tight safety margin of 0.1°C above 1.5°C that was considered in AR6. The ScenarioMIP specifications include the VLLO scenario that requires to explore the fastest and deepest emission reductions that are plausible without threatening sustainability constraints. This scenario has the potential that the temperature by 2100 is below the level in 2025 but in between the 1.5°C guardrail (plus the 0.1°C extra margin) would be exceeded. Therefore, in such a scenario the temporary overshoot is already happening. The following discussion of the existing literature relies on the assumption that the overshoot era still lies in the future; only at the end we will get back to this issue when discussing future research.

The term overshoot scenarios means that a long-term climate target is temporarily exceeded. The long-term target in most cases is a carbon budget, CO_2 concentration or the global mean temperature change above pre-industrial levels. Thus, overshoot implies that after a peak, e.g. in cumulative global CO_2 emissions, a decline process is induced that steers the modelled system to fulfil a given target, e.g. a carbon budget, by a certain point in time, e.g. 2100. The carbon budget approach has gained substantial interest due to its close relationship with the global mean temperature change compared with pre-industrial levels (Zickfeld et al. 2009). The in-depth investigation of complex climate models as well as the statistical analysis of historical data has found for a broad set of future emission scenarios that global mean temperature in a year is closely related to the cumulative CO_2 emissions up until that year and that zero-emissions stabilize global mean temperatures while positive (negative) net-CO_2 emissions lead to increases (decreases) of the global mean temperature (Matthews et al. 2009). Thus, emissions and removals of CO_2 can be treated symmetrically. The linear relationship also allows straightforward derivation of remaining carbon budgets given a target and the emissions to date (Rogelj et al. 2019, Lamboll et al. 2023). This result has been corroborated for the various SSP emission and land-use pathways and approved by the IPCC in the AR6. It must be added that these scenarios not only comprise CO_2, but also other GHG, aerosols and effects from land-use changes. To avoid confusion, if net-CO_2 emissions are zero and the cumulative emissions are constant, the CO_2 concentration decreases because the terrestrial vegetation and the oceans are expected to remove CO_2 from the atmosphere until an equilibrium is reached. If the CO_2 concentration is stabilized at an elevated level the thermal inertia of oceans would lead to continuously increasing temperatures (Matthews et al. 2009). Thus, the overshoot in CO_2 concentration does not necessarily imply overshoot in global mean temperature.[10]

The temporary overshoot of long-term climate targets is often related to a delay or even deterrence of emission mitigation action that is not followed by timely removal of CO_2 from the atmosphere. Since there is no binding enforcement mechanism and carbon removal is costly the risk of insufficient removal in the future is justified. A hedging strategy against this risk is stronger near-term emission reductions. This is related to the concept of a moral hazard to

[10] A steep increase of the CO_2 concentration would lead to a steady increase of global mean temperature until the new equilibrium is reached. Thus, stopping CO_2 concentrations from increasing and stabilizing them at a level higher than the pre-industrial level will very likely not result in decreasing temperatures.

reflect the problem that plans of today to reduce emissions in the future require an enforcement mechanism to keep up with promises in 2100 that were made today. The intertemporal nature of the problem requires a strong and binding commitment today about carbon removals in the future. Otherwise emissions today will likely not be offset in the future. Such commitments require specific institutional settings and governance structures, such as funds that are fed in early periods and tasked with specific purposes such as financing CDR deployment.

Historically, the debate about timing of emission reductions, or equivalently the optimal allocation of a fixed carbon budget over the 21st century, is discussed since the 1990s (Wigley et al. 1996). Back then standard mitigation scenarios assessed scenarios limited to CO_2 concentrations below 550ppm (a doubling as compared with pre-industrial levels), which led to temperature increases that are clearly beyond the limits agreed on in the Paris Agreement. Also, this moderate target allowed substantial positive net CO_2-emissions throughout the 21st century and led to continued increase of global mean temperatures throughout the 21st century and beyond. The focus on CO_2 concentration originated from the formulation of Art. 2 of UNFCCC that indeed aimed at stabilization of GHG concentrations.[11] The Copenhagen Accord and the Paris Agreement shifted interest towards targets that stabilize long-term temperature and also strengthened the long-term targets in terms of expected long-term temperature. The assessment of long-term temperature targets also required the inclusion of non-CO_2 GHG and aerosols into policy frameworks. However, since CO_2 remains the major driver of climate change the carbon budget has been established as a proxy for temperature targets.

Main arguments for the delay of mitigation into the future were the time preference rate[12], the inertia of the capital stock and the exogenously assumed improvements of technologies that allow for cheaper emission reductions in the future. The most important arguments against were the additional irreversible warming, the associated climate risks, the uncertainty to radically change course in the future, and the endogeneity of technological change in the future that requires early investments in new technologies. For example, technology learning requires early deployment of the corresponding technologies to drive down the costs and make the technologies more competitive.

The climate target in the Paris Agreement increased the need to investigate scenarios with much lower emissions and even scenarios with net-negative CO_2 emissions. This leads to efforts to include various carbon removal options into the analytical framework of IAMs and, furthermore, the integration of energy and land-use models, combined with the target in the Paris Agreement resulting from growing concerns about the severity of impacts of climate change have increased the interest in assessing scenarios complying with the 1.5°C and well below 2°C objective. Since these scenarios with low-stabilization targets would require very strong near-term emission reduction, the question of temporarily overshooting the target has been discussed.

A major question has been the magnitude and duration of temporarily overshooting such a carbon budget, which is strongly linked to temperature overshoot (see also Bauer et al. 2023). While the duration is measured in years, the overshoot magnitude can be measured in physical units like the maximum exceedance of the carbon budget in Gt CO_2. Most studies compute overshoots with a duration until 2100, but the maximum overshoot can vary between different scenarios (see e.g. Riahi et al. 2021). Given this constraint on the duration, the magnitude of the

[11] Most Integrated Assessment Models in the 1990ies and early 2000s focused on CO_2 only. The whole suite of GHG was included step-by-step in the following years.

[12] The time preference rate is a metric with which values are made comparable over time. The argument is that due to impassion goods enjoyed in the more distant future are valued less than goods enjoyed today (in German "Minderschätzung zukünftiger Bedürfnisse"). The time preference rate influences the time path of emissions, since a higher time preference rate will lead to delaying costly emission reductions into the future.

overshoot is computed endogenously. A limitation of the overshoot magnitude can be motivated by a number of arguments. Basically, the avoidance of additional climate risks, the intergenerational equity argument, incl. the time preference rate, and the implementability of large-scale carbon removal activities are among the most prominent arguments discussed. The overshoot-debate reiterates several arguments of the earlier discussions.

The specifications of the low temperature scenarios give guidelines on the general shape of the emissions, the temperature profile and constraints on carbon removal deployment. The temperature outcomes are not harmonized between the different ScenarioMIP scenarios. From an analytical position it is useful to think in pairs of scenarios that reach the same long-term climate target, but differ in the assumption about the overshoot. Comparison of such pairs of scenarios are useful to quantify the importance of the overshoot. More specific projects and MIPs under the CMIP7 process can be devoted to this issue. For example, the Horizon Europe Project RESCUE will run ESMs to evaluate such pairs of scenarios that are provided by the REMIND-MAgPIE team.

An investigation of Paris-compatible scenarios with differing degrees of overshoot can be related to the carbon price profile over time. Although the ScenarioMIP specifications do not investigate harmonized pairs of overshoot and non-overshoot scenarios, the implementation of scenarios with varying degrees of overshoots will also, with very high likelihood, be related to the time path of carbon prices.

The level of ambition to limit CO_2 emissions, reduce them and even reach net-negative emissions by sufficient CDR deployment can be reflected in the carbon price and its time path. A socially optimal solution is characterized by equal marginal cost of emissions reductions across all sectors, countries and gases. Marginal abatement costs increase with stronger policy ambition and, thus, lower emissions require measures with higher marginal abatement costs. Assuming that a carbon price is implemented that covers all sectors, gases and regions, the carbon price level makes the policy ambition comparable over time and across scenarios and models.

The time profile of the carbon price reflects the development of the policy ambition. Assuming that over a given time horizon (e.g. until 2100) an exogenous carbon budget constrains the cumulative CO_2 emissions the overshoot dynamics results from the carbon price path. A price that starts low and increases strongly reflects low policy ambition in the near term that increases over time. This low policy ambition can lead to the exceedance of the carbon budget, which then requires stronger policy ambition in the longer-term to balance the carbon budget by the end of the time horizon. A special case is that the carbon budget is treated as a finite resource. In this case the CO_2 prices would increase with the market interest rate, also known as the Hotelling rule owing to the optimal use of a finite mineral resource over time.[13] The Hotelling model is a canonical part of economic theory. The fundamental difference between a mineral resource and a carbon budget is that carbon removal technologies allow to first overshoot the carbon budget and later, by realizing net-negative emissions balance the carbon budget. A mineral resource, however, cannot be overused like a carbon budget for obvious physical reasons. Herein lies the crucial challenge to enforce a carbon budget over time. Nonetheless, the Hotelling-rule still applies for the CO_2 price time path despite the overshoot (see e.g. Strefler et al. 2021a). The resulting emission trajectory can feature huge net-negative emissions and huge overshoots. If the carbon budget overshoot should be limited the carbon price would rise in the near term and level off as soon as the carbon budget is exhausted and carbon neutrality is

[13] Hotelling model refers to a standard model in resource economics. The basic result is that the price of a finite, non-renewable resource, for example a mineral resource, increases at the interest rate. This result rests on very idealized assumptions. The carbon budget can be compared with a non-renewable resource. The crucial sticking points are that the carbon budget can be enlarged, while a finite mineral resource cannot. Also, the carbon budget can be overshot, which is impossible for a finite resource.

achieved (i.e. carbon removals offset gross carbon emissions). An analysis of the relationship of carbon budget, carbon removal technologies and the carbon price has been provided in Strefler et al. (2021a). An alternative implementation can assume that net negative emissions are not remunerated, while the price for emissions and removals that only offset the gross emissions still grow exponentially (Bauer et al. 2023).

An important point in this debate is the notion of the market interest rate. It is debatable whether the market interest rate is a reasonable proxy for the social choice problem of a carbon price time profile. One can argue for a categorial difference between the social and the private discounting rates that has been mentioned in the introduction. The difference basically means that individual decision making relies on higher discount rates such as the market interest rate that reflects high individual rates of pure time preference and also high-risk mark-ups. The policy maker can accept high discount rates as an expression of the freedom of individual choices and behaviour, but at the same time argue that long-term collective decisions should be undertaken assuming lower discount rates that represent the public priorities and preferences.

This debate goes back to the evaluation of future economic damages caused by CO_2 emitted today. Nicolas Stern argued for a pure rate of time preference of 0.1%/yr for ethical reasons, whereas at that time William Nordhaus argued for 3%/yr referring to empirical estimates in capital markets. Later Nordhaus changed the position towards a lower pure rate of time preference that is actually decreasing (Arrow et al. 2013). This follows from the acknowledgement of uncertainty that give equal probability weights to a low and a high discount rate. As a result, the expected discount rate starts at the upper level and develops towards the lower level. The main sticking point in this debate is the intertemporal evaluation of damages over very long time horizons. This is a main issue in cost-benefit analysis IAMs (see Chapter 2), in which cumulative emissions are derived endogenously and the notion of a carbon budget as a policy constraint is not applicable. The discussion in this section is about the exhaustion and reproduction of a carbon budget over a given time horizon, thus the application of the CEA approach without considering the damages.

In the context of a carbon budget with potential overshoot a lower discount rate implies lower near-term emissions, due to stronger near-term mitigation efforts, and consequently a smaller overshoot (if any). This theoretical finding has been corroborated by Emmerling et al. (2019) in a sensitivity study using a relatively simple IAM and comparing it with an analytical model. However, this study did not distinguish between the public and private discounting rates. Thus, lower discount rates not only increased the policy ambition in the near-term, but also lowered the cost of capital-intensive technologies. The study also did not question the applicability of the Hotelling framework in the context of an overshoot. The authors question the magnitude of the carbon budget overshoot, but as a consequence they vary the discount rate (or more precisely the pure rate of time preference) whereas the more direct change in assumption would have been to limit the overshoot directly and investigate the impact on the carbon price time profile. In that case, the qualitative shape of the carbon price trajectory changes, where a phase of increasing prices is followed by a more stable or even decreasing CO_2 price as investigated by Strefler et al. (2021a) and corroborated by Riahi et al. (2021).

A major shortcoming is the conflation of the overshoot dynamics with the carbon removal trajectory, which is related to the carbon price. In Strefler et al. (2021a) as well as Bauer et al. (2023) constraining the overshoot leads to higher carbon prices in the near term and, therefore, to lower near-term gross CO_2 emissions and higher near-term carbon removal before 2050. This implies that avoiding an overshoot means stronger reductions of gross emissions and more reliance on near-term CDR although long-term needs for CDR are lower than in the case with full

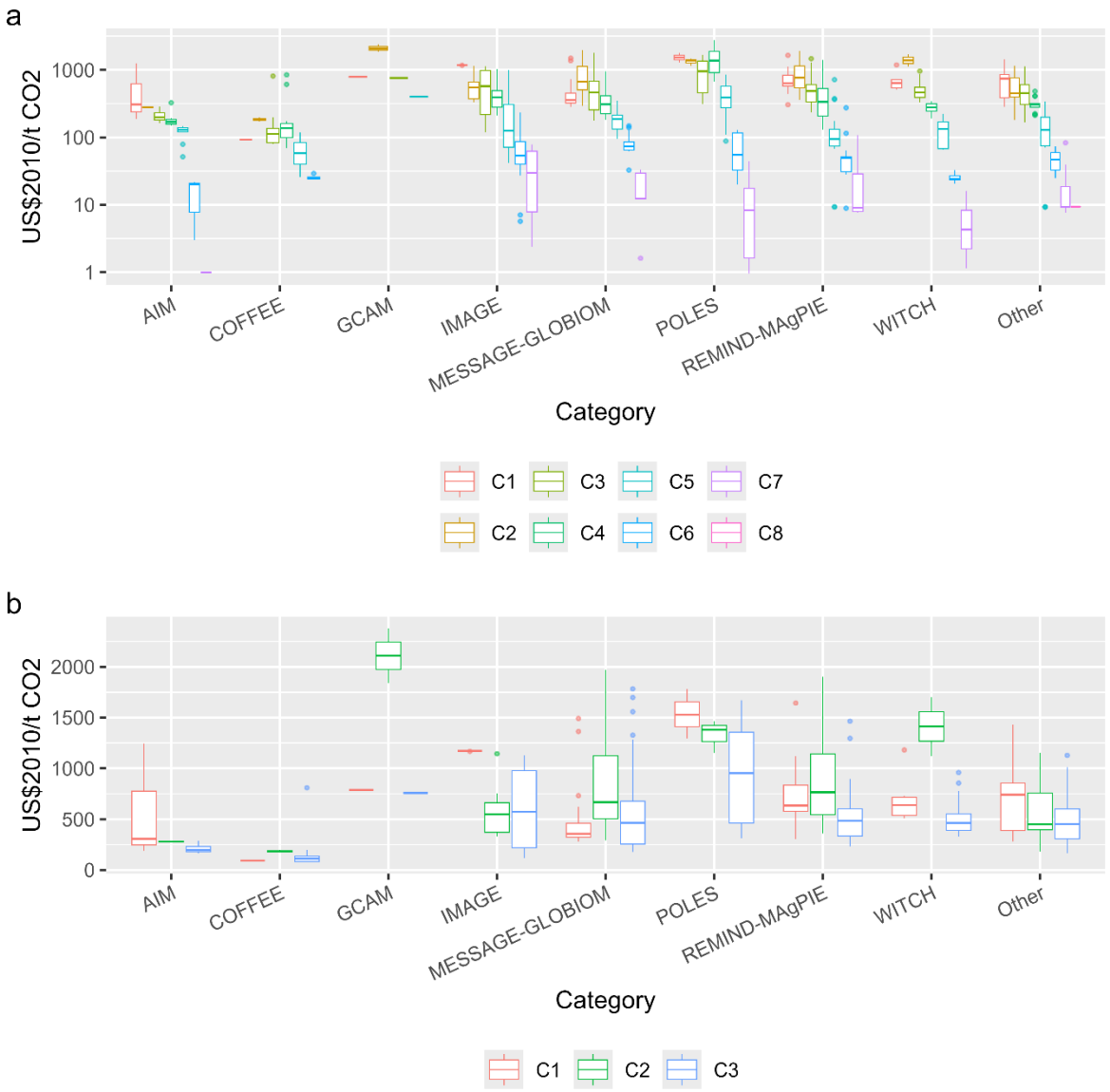
overshoot. The conflation lies in the fallacy that in case of only restricting the overshoot the actually lower long-term CDR (due to a lower carbon price) would also reduce the near-term need for CDR. However, this is in contradiction with the stock pollution nature of the climate change issue, which is most directly expressed in the global carbon budget and the resulting carbon price dynamic. We note this fallacy because in the literature this argument is often made or the higher CDR deployment is simply not mentioned. It is, nonetheless, only true if only the assumption about the permissibility of the overshoot is varied. If also additional assumptions on socioeconomic drivers and energy and food demand are varied the overall demand for CDR can be reduced because gross emissions can be reduced more easily. This will be seen in the ScenarioMIP scenarios below (see Chapter 6), while the AR6+ scenarios generally show this behavior.

For the analysis of the AR6+ scenarios, we investigate the scenarios with overshoot. We measure the overshoot magnitude by deriving the difference between peak cumulative emissions and end-of-century cumulative emissions and match this with the maximum CO_2 price, which is in most cases reached by the end of the century. Additionally, we filter the scenarios for cases that feature at least 1 $GtCO_2$ difference to classify them as overshoot-scenario. 432 scenarios comply with these criteria.

Figure 7 shows the distribution of average CO_2 prices 2050-2100 in log-scale (upper panel) for the IPCC scenario categories C1-C8 for various models that prominently served for the AR6 report. The lower panel shows a selection of C1-C3 in normal scale. Most models show lower CO_2 prices for the C1 scenarios (with low or no overshoot) than for the C2 scenarios (with medium or large overshoot). This finding corroborates the general argument about the CO_2 price profiles for achieving a long-term climate target with or without overshoot.

Figure 7: Distribution of average CO_2 prices 2050-2100 across IPCC AR6 climate target categories and for different models

The whiskers indicate the overall range, the 25% and 75% quintiles and the median. The upper panel shows all scenarios categories C1-8 with log-scale; the lower panel only the low emission scenario categories C1-C3 with a normal scale.



Source: own compilation based on AR6+ database.

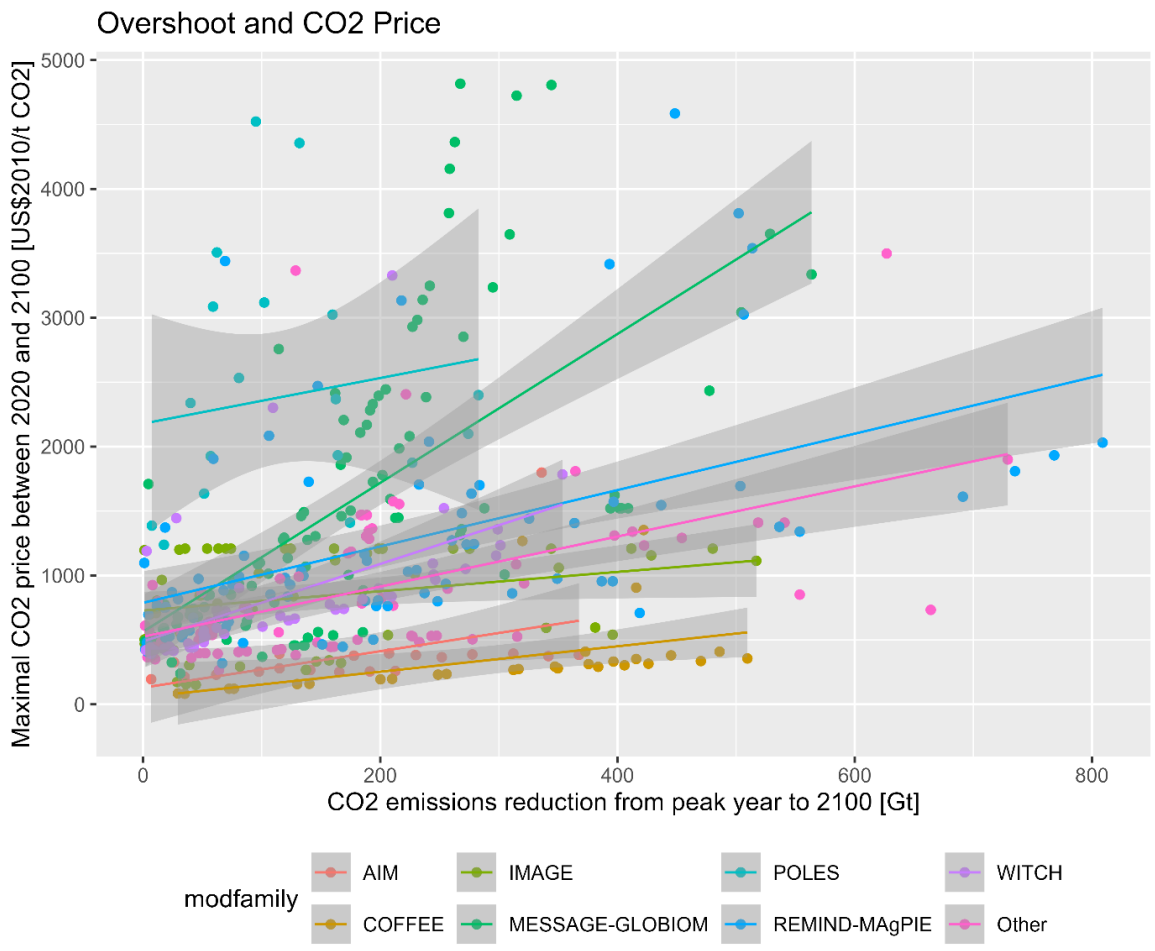
These prices are substantially higher than the marginal costs of carbon removal assessed in techno-economic studies that reach up to 200-300 USD/tCO_2 (Fuss et al. 2018 for an overview of literature values; a more recent estimate with substantial uncertainty ranges is reported in the State of CDR report[14], page 152). The main reason is that the demand for carbon removals reaches the limits of the potentials that are constrained by geological, geobiophysical, sociopolitical and technoeconomic constraints. The result would be substantial rent incomes in the private sector, if the remuneration for removals exceeds the removal costs.

[14] https://pure.iiasa.ac.at/id/eprint/19787/1/The-State-of-Carbon-Dioxide-Removal-2Edition.pdf

In the AR6+ database this issue can be identified (see Figure 8). The maximum overshoot reaches 800 $GtCO_2$, but 90% of scenarios stay below $400GtCO_2$ (392 out of 434). Maximum CO_2 prices can reach extremely high levels due to outliers, whereas 80% remain below 1500 USD t/CO_2. Such very high prices have been also reported by Riahi et al. (2021). Besides that, it is worth to note that the database reveals substantial differences between models (so called 'model fingerprint'). The REMIND-MAgPIE model range lies in the middle across scenarios.

High CO_2 prices towards the end of the century that are associated with huge carbon removal deployment are subject to issues of financial and fiscal viability, since revenues of pricing carbon emissions might not be sufficient to finance carbon removals. If carbon removals are remunerated at the same price level like gross emissions, net-negative CO_2 emissions would automatically require additional funding, because revenues from gross CO_2 emissions could only provide finance for CDR to reach net-zero CO_2 emissions. Thus, from a fiscal perspective additional funds would be needed to reach substantial net-negative emissions. In the model context the optimal solution is not confronted by such fiscal implementation issue, but in the real-world policy context this can be considered an issue, if the removals need to be financed from public budgets. This is a fundamental policy issue that has been raised by Bednar et al. (2019) and Strefler et al. (2021). These financial demands can reach substantial levels of several percentage points of GDP in 2100; see Strefler et al. (2021, Figure 4).

Figure 8: Maximum CO_2 prices between 2020-2100 against carbon budget overshoot based on 434 scenarios from the AR6+ database



Source: own compilation based on AR6+ database.

A recent study by Merfort et al. (2024) investigates the possibility to separate the targets for emissions and removals and therefore address the issue. If the financial gap could not be closed within each period, the consequence would be that savings from previous periods, potentially financed from carbon pricing revenues, could finance a fund for future carbon removals. If such a solution cannot be implemented, it would be necessary to finance carbon removal by different sources such as the public budget. If the markets could be separated the costs paid for removals could be substantially reduced, while the quantities are only moderately reduced. The separation could be implemented by an auctioning system similar to renewable energy mandates.

For a new set of emission scenarios and updated climate scenarios, the shape of the carbon price trajectory is crucial. The scenario specifications of ScenarioMIP consider not only very different long-term climate targets, but also a broad range of differences regarding the overshoot. While the specification of the VLLO scenario requires strong sustainability constraints that limit CDR deployment, while achieving low temperature changes, the VLHO scenario allows a substantial overshoot. These variations in the scenario specifications will be associated with very different CO_2 price profiles.

Major open questions regarding the CO_2 price path are related to the following research directions:

1. The plausibility of very high long-term CO_2 price levels and the question, whether models represent all reasonable options and the potential implications for rent incomes.
2. The rate of increase or potential decrease of the CO_2 price and the carbon price trajectory post-peak of cumulative emissions.
3. The institutional requirements, governance and financing of carbon removal in high overshoot scenarios and the potential of separating markets for CO_2 emissions and CO_2 removals.
4. Assessment of uncertainties of CDR technologies and the effectiveness against leakage and how this uncertainty influences policies.
5. Implementation of distinct private and public discount rates and systematic investigation of overshoot dynamics and investment patterns, see next Section 4.3.

The ScenarioMIP specifications are not aiming at the direct comparison of stabilization scenarios with different overshoot specifications. Such comparisons are highly interesting, but will require more dedicated model comparison exercises. Using the REMIND-MAgPIE model framework such comparisons are undertaken in the Horizon Europe project RESCUE. A more systematic investigation of specifications on carbon price development (point 2 above), carbon price discrimination (point 3), and distinct discount rates (point 4) is important, but is not planned in projects. Within the RESCUE project timeframe, a comparison between carbon price trajectories could be pursued.

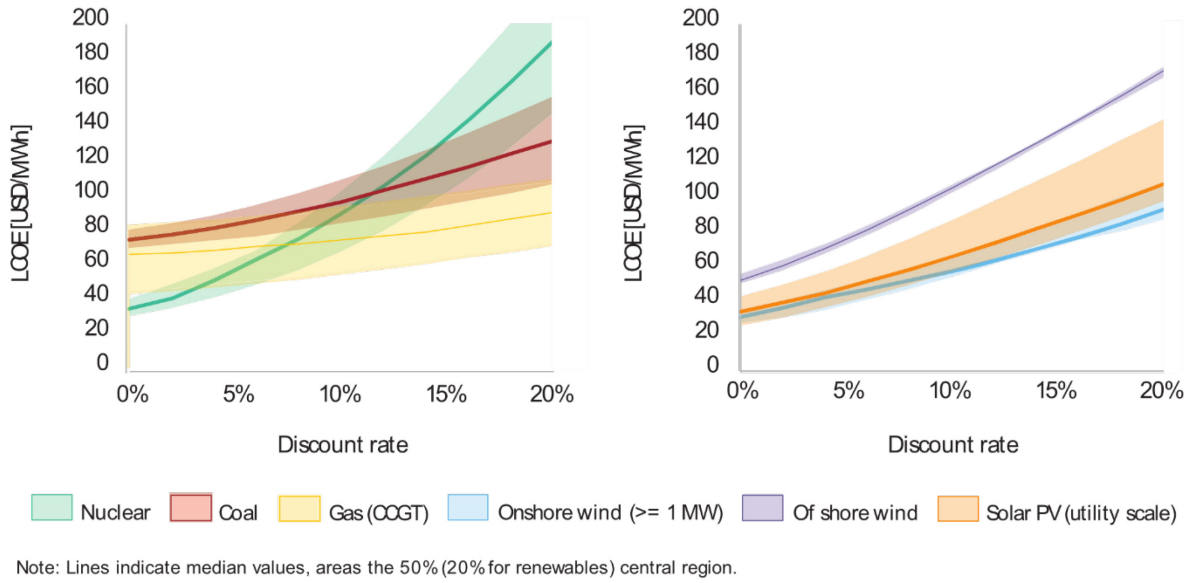
4.3 Differentiated risk premia, investments and transition dynamics

The cost of capital is an important determinant for the supply cost of energy. Renewable energy supply features, with the exception of bioenergy, high shares of capital costs as fuel costs are irrelevant. Thus, the cost of capital exerts strong influence on the final cost of energy. Fossil fueled energy supply technologies are much less sensitive to the cost of capital. For example, the 2020 edition of the assessment of the levelized cost of electricity by the International Energy Agency (IEA) and the Nuclear Energy Agency (NEA) shows how the costs per unit of produced electricity change with the cost of capital, or the discount rate (see Figure 9). For low discount rates, onshore wind and solar PV are competitive with fossil fueled technologies. It should be

noted that the capital cost is relevant for both the capital during the construction phase and during the operation. Since wind and solar electricity equipment can be installed in shorter time than thermal power plants, these technologies have a systematic advantage during the construction phase, but more relevant is the cost of capital that needs to be recovered during the operation phase that is much longer.

A change in the overall discount rate (or the pure rate of time preference) also affects the cost of capital and therefore the costs of emission reductions (Hirth and Steckel 2016). If the discount rate is adjusted for ethical reasons, it would also interact with the dynamics of the energy sector investments. This effect would be seen in process-based IAMs, because here the investments are calculated explicitly. In CBA-IAMs, this is largely irrelevant because the costs of emission reductions are represented by marginal abatement cost functions with no explicit investment dynamics.

Figure 9: Levelized Cost of Electricity per technology depending on the capital cost (discount rate) in real terms, i.e. inflation effects are neutralized



Note: Lines indicate median values, areas the 50% (20% for renewables) central region.

Source: IEA/NEA (2020, p. 84). License: CC BY 4.0

The empirical research on capital financing costs has so far mostly focused on power sector generation technologies. We are not aware of systematic studies that go beyond and investigate also infrastructure investments (e.g. grid investments), non-electric energy supply and conversion technologies, as well as demand side technologies. Moreover, there is surprisingly little empirical research on the overall financing costs of capital investments and the risk mark-ups that are charged (and paid) in different countries.

Since investments are a key driver of the transformation towards a low-emissions and potentially even a net-negative society, financing costs are potential barriers. It is also very important to understand the causes and determinants for the mark-ups. A recent study by Calcaterra et al. (2024) investigated the effect of capital costs differentiated between technologies and across countries. The first modeling results show that the effect of capital cost mark-ups that decrease and converge towards a world market level for the electricity sector are larger in developing countries than in developed countries and in scenarios with weak climate policies. The reasons are the relatively high capital cost mark-ups in developing countries where the convergence towards a world market level would be greater and the relative importance of

the capital costs is more important than in stringent mitigation scenarios. If a substantial carbon price is implemented that also rises over time, it becomes the dominant factor for investment choices and dwarfs the role of the different costs of capital. It should also be noted that lower capital costs lower the dependency of energy sectors on fossil fuels, which is important for the energy security of fossil fuel importing countries. The study by Calcaterra et al. has a serious short-coming as it only investigates relative differences between scenarios, but does not investigate the absolute effects of the deployment of technologies and the impact on total emissions.

Higher financing costs can be caused by domestic regulatory factors and general business uncertainties. Country mark-ups can also be related to more international factors such as sovereign default risks, exchange rate risks, etc. Reasonable and reliable modeling of capital market barriers needs to work towards a comprehensive and differentiated representation of financing cost mark-ups. Endogenous dynamics of capital market distortions need to carefully attribute risk mark-ups to the right domestic and international drivers and causes. Especially, risk mark-ups carry the twin-nature of being symptoms of underlying imperfections and distortions and can also be the cause for misallocation of investments. Policies based on incorrect cause-effect representations could turn out counterproductive. E.g. if domestic regulatory uncertainties related to poor governance are the cause for risk mark-ups in a country, providing international grants to the same government for a misguided motivation to overcome international capital market imperfections would probably lead to inefficient outcomes. Therefore, the choice of policies needs to be carefully tailored given the reasons for the risk mark-ups.

In future research, the differentiation of capital costs needs to be applied to all investments. If only electricity sector investments are modeled with capital cost mark-ups, the use of electricity would be subject to a competitive disadvantage compared with other final energies as well as broader capital investments. First modeling tests also raise the question, whether the model approach of a simple risk premium is sufficient. In pre-liminary investigations we see that the effect on the macroeconomic growth dynamics is relatively small. More elaborate modelling approaches need to be developed that not only reflect the capital market risks of capital market imperfections, but also the inefficiency allocating investments. This modelling approach would not use risk-ups as an exogenous input parameter, but model capital market distortions that give rise to capital cost mark-ups as endogenous variables. This modeling technique is novel and requires more efforts, but could lead to very different policy conclusions.

Since renewable energy investments in the electricity sector are a crucial strategy in developing countries and emerging economies, international cooperation can help to formulate policies that overcome investment barriers and reduce the risks of such investments and help to crowd-in private investments and attract more private finance that follows public interventions. IAMs can help to identify efficient and effective policy packages of international finance that lead to high emission reductions that are caused by huge investment mobilization achieved with limited public funding from donor countries. This research is underdeveloped, but IAMs can be used in this direction.

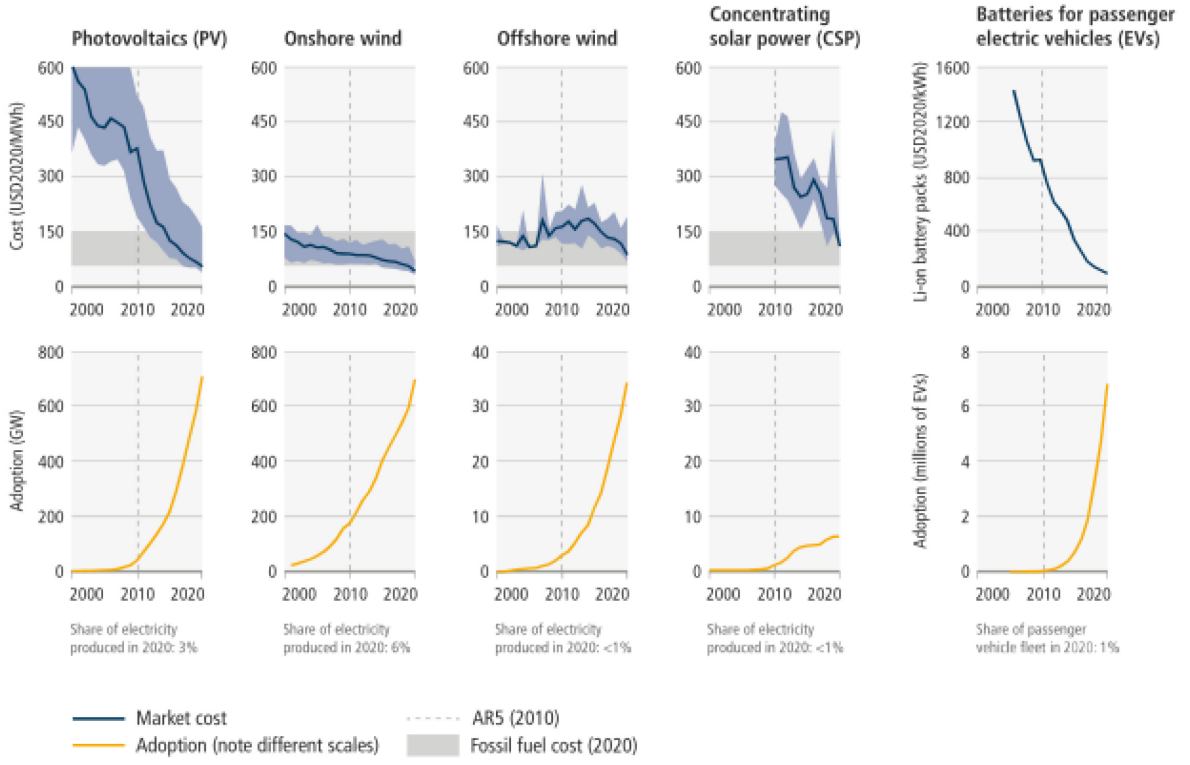
Another interesting issue would be to couple the mark-ups to the monetary policies of central banks that react to inflationary signals due to increasing energy and food prices. The interesting point would be to understand whether central banks that blindly follow their mission to fight inflation could have dysfunctional effects by increasing interest rates that undermine investments into low-carbon energy supplies. This would further increase energy prices and drive inflation, and in turn lead to central banks responding with further increases of interest rates. In such a situation the imposition of strong climate policies can turn into a struggle over

inflation between governments and central banks. The policy response by the central banks, including the ECB, to increase interest rates as a response to increasing energy prices following the neo-imperial invasion of Russia into neighboring Ukraine shows that Central Banks work according to these patterns.

4.4 Cost Reductions of Renewables, Grid Integration and other Low Carbon Technologies

The digression of investment costs of renewables and other low carbon technologies has by far outpaced the development of fossil fueled technologies as well as nuclear power. Especially the cost reductions of Solar PV and Batteries (important for buffering variable renewable electricity and the electrification of the transport sector) was remarkable. This has been acknowledged by the IPCC in the SPM of the AR WG3 report (see Figure 10). The deployment of these technologies has been mostly triggered by public support programs in the past, but renewable electricity production is competitive with fossil fueled alternatives in many parts of the world.

Figure 10: Development of Levelized cost of electricity (top row) and capacity development (bottom row) for renewable electricity supply and batteries for vehicles until 2020

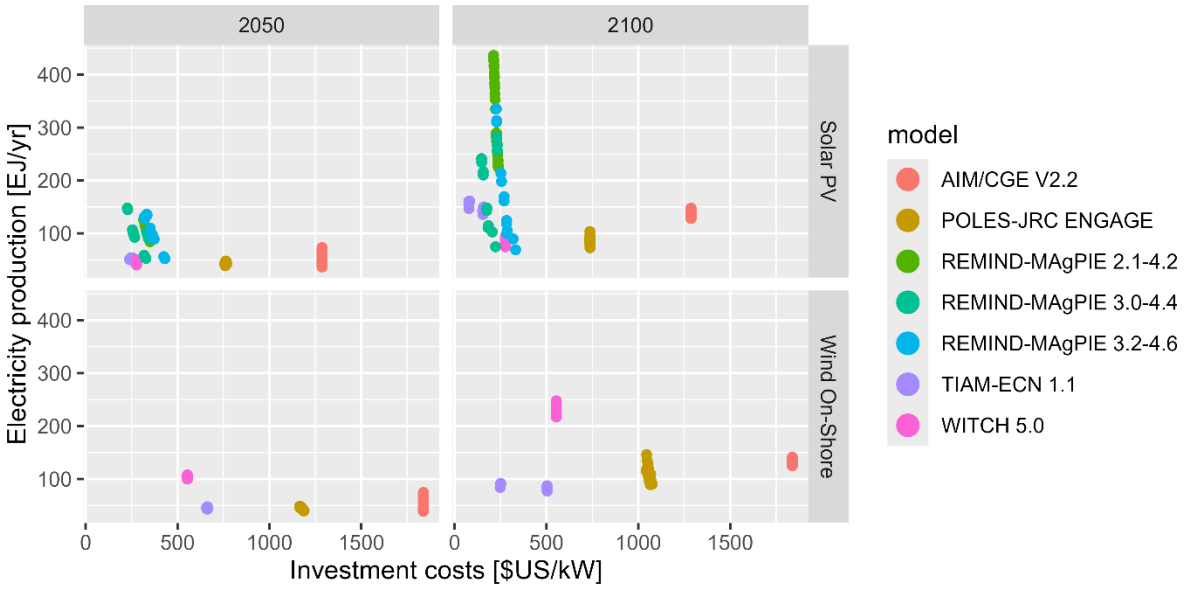


Source: IPCC AR6 WG3, SPM Figure SPM 3.

This dynamic development will lead to substantially lower CO_2 emissions in baseline and weak policy scenarios. In the context of ScenarioMIP, it is expected that this change to a technoeconomic situation that is much more optimistic than previously expected will reduce the uncertainty space of future emission pathways. For instance, it is not expected that even high emission scenario narratives such as SSP3 “Regional Rivalries” and SSP5 “Fossil Fueled Development” with full roll-back of all climate policies will reach the very high emission levels of the 2017 edition of the SSPs (Riahi et al. 2017 and Bauer et al. 2017). In ScenarioMIP attention is paid towards technoeconomic assumptions of energy technologies. So far, the investment costs

assumed have attracted less attention during the assessment process. An investigation of the AR6+ database reveals very strong differences across models (see Figure 11). The clustering around certain values reflects the fact that these assumptions are updated in low frequency. However, more important are the huge differences that have been found. Also, many models have not reported the assumptions and thus are not included in the AR6+ database. It should be noted that the REMIND model only reports the investment cost of wind power, not onshore wind separately.

Figure 11: **Scatterplot of electricity production against investment costs for solar PV and onshore wind in 2050 and 2100 for models that reported the information to the AR6+ database**



Source: AR6+ database.

Moreover, the improved techno-economics of renewable electricity generation and storage technologies will improve the feasibility of low and very low emission scenarios. This is not only due to the cost, but also due to the extraordinary fast ramp-up of capacities and the integration into existing electricity supply systems.

A recent study by Luderer et al. (2022) shows that electricity could become the lowest-cost final energy supply source in 1.5°C scenarios, if historic learning rates that reduce investment costs will continue with increased deployment and CO_2 pricing increases the cost of non-electric final energy supplies that depend on fossil fuels. For the broad diffusion of renewable electricity, it is not only important that the electricity supply is cheap and plentiful, but also that the fossil fueled alternatives are charged with a carbon price. This combination will lead to broad adoption of electricity-based technologies in end-use sectors such as heating, process heat, heavy industries and transportation. The broad electrification can also help to keep the demand for bioenergy low. The supply of hydrocarbons can also profit from green electrification by providing the energy input for the production of e-fuels and synthetic gases, which are important for hard-to-abate applications in industry and transport sectors. Moreover, affordable renewable electricity can also support the achievement of SDG6 of access to clean energy.

Finally, electricity is a crucial input for novel CDR technologies such as Enhanced Weathering, Direct Air Capture and Ocean Alkalinity Enhancement (e.g., Broehm et al. 2015, Strefler et al. 2018).

4.5 Feedback of Climate Impacts and Damages on Economic Development

The mitigation scenarios developed with process-based IAMs in most cases do not integrate feedbacks of climate change on the socioeconomic and sociotechnical development. For instance, the SSPs have been designed to not include such feedbacks: "SSP scenarios presented here do not consider feedbacks from the climate system on its key drivers such as socioeconomic impacts of climate change." (Riahi et al., 2017, p. 155). Also, the specifications for the new set of scenarios for ScenarioMIP explicitly exclude the integration of climate feedbacks and assumes the effects to remain frozen at the level of 2020. This also includes the effect of CO_2 fertilization in the agricultural sector.

There have been some exceptions. In the AR6 database, there is only one set of scenarios containing climate damages and feedbacks on GDP. There are six scenarios of the NGFS2 project of the REMIND-MAgPIE model. The damages are only added as a diagnostic after the model run to quantify the reduction of GDP depending on the corresponding warming. Thus, the explicit feedback on the macroeconomic dynamics is not modelled in IAMs, which could add negative GDP responses through macroeconomic transmission channels. This is methodologically sound because the estimates of the GDP response function already comprise the feedbacks and thus no double counting of the macroeconomic feedbacks occurs. An integration into the IAMs would require to neutralize the feedbacks in the estimated parameters. Otherwise the IAM result would contain double counting effects.

The publication by Drouet et al. (2021) and also Bauer et al. (2023) applied the diagnostic approach. Both studies are based on the econometric study by Burke et al. (2015) which estimated parameters of functions, where variations of GDP responded to temperature variations based on historic data. Both studies also included additional impact categories in different sectors. Still, the impacts on economic development do not affect the transformation pathway from which the energy demands and supplies are derived. Thus, the twin pressure of mitigation and damage is not considered simultaneously. The studies showed substantially higher and long-lasting GDP reductions, if the persistence of GDP shocks is long (e.g. 15 years). A more conceptual study on the transmission channels of climate damages in the macroeconomic system and the implications for the persistence of GDP reductions has been provided by Piontek et al. 2018.

The exclusion of feedbacks in process-based IAM scenarios needs to be qualified. Since global temperature has already increased and socioeconomic systems have experienced impacts and damages that are attributable to climate change, the historic data record already includes the feedbacks and therefore the calibration of IAMs to historic data also assumes these changes of socioeconomic variables (e.g. reductions of GDP caused by historic warming). Thus, as mentioned above, the exclusion of climate feedbacks means to freeze the feedbacks at the level already experienced up until today. A full exclusion of the feedbacks would require to derive a counterfactual scenario, in which climate change has had no impact on socioeconomic variables. That would imply, however, that the scenario would deviate from historic data and, thus, a comparison with historical data would identify gaps.

With a perspective on ScenarioMIP, the new emission scenarios will exclude additional climate impacts and damages. Implicitly, it will include the climate impacts that the global economy already experienced. The ScenarioMIP exercise is designed to deliver information for the Earth System Models and the Impacts, Adaptation and Vulnerability modelers. Thus, the scenario design specifications exclude additional feedbacks from climate change. It is a major aim of ScenarioMIP to deliver information in due time to facilitate a full assessment across the three

IPCC Working Groups for the Seventh Assessment Report (AR7) to inform the Second Global Stocktake.

Consequently, the feedback effects of climate change on the transition pathways will be a major research topic in the broader research community. For IAMs this includes the feedbacks on the energy demand and supply as well as the agricultural production sector (incl. the CO_2 fertilization effect). A second strand of research investigates the macroeconomic feedbacks on the transformation pathway.

In the REMIND-MAgPIE model, the expected reduction of GDP would lower the demand for energy and food and thus, very likely, decrease GHG emissions. The lower GDP would, however, also have detrimental effects on the capacity and capability to mitigate GHG emissions. The main reasons are related to a slowdown of the overall development and modernization process. First, developing economies feature decreasing expenditure shares for energy and agricultural products. Lower expenditure share for these primary products indicate decreasing dependency on them. With slower increase of income also the expenditure share would decrease slower or even stagnate and thus the dependency would remain higher. Consequently, the burden of transforming the energy and the agricultural production sectors is relatively higher and, therefore, the mitigative capacity is lower. The second main reason relates to the consequence that lower per-capita income also draws savings down in absolute terms; this implies that less financial means are available to finance investments. The lower consumption level also implies a lower willingness to save at the expense of consumption. This lowers the ability of society to mobilize additional savings which is a precondition to finance the transformation of energy and agricultural production. The increasing scarcity of savings for financing the investments puts limits to the capacity for transformation towards capital intensive low-emitting technologies and also deploying carbon removal technologies.

The delayed modernization due to the macroeconomic feedbacks will be stronger the lower the per-capita income, the higher the financing cost of capital, and the higher the GDP reductions from global warming are. Thus, Least Developed Countries would be probably most affected by the macroeconomic feedbacks. The interaction of macroeconomic feedback effects and the mitigative capacity has not been investigated systematically so far.

The inclusion of the GDP responses to climate change can have additional feedback effects that are worth further investigation to inform policy makers. First, the lower GDP would put public budgets under pressure, which would in turn lower the capacity to mobilize public money for mitigation and adaptation measures. Second, the reconstruction of damages demands capital leading to crowding-out effects with other investments, incl. mitigation. Third, the reduction of GDP would also reduce income growth, which undermines poverty eradication (SDG1).

The inclusion of impacts into the IAMs raises a great deal of new research questions concerning equity and the contribution of nations to the global public good of a stable climate. A key challenge is to implement different mechanisms for nations to find solutions for the public good problem. For example, the concept of Lindahl-equilibria for the voluntary contributions to a global public good that also includes international financial mechanisms can be tested. Also, equity could be represented in asymmetric weighing in deriving region specific Social Cost of Carbon in order differentiate between different countries. IAMs like the REMIND-MAgPIE model are equipped to implement and test such alternative mechanisms. This can bring highly valuable insights into the interplay of welfare economics and political economy in the international context.

4.6 The Impact of Poly-Crisis on Transformation Pathways

The contemporary global situation is affected by multiple crisis that affect the overall socioeconomic and sociotechnical development as well as the broader geopolitical context within which climate policy is happening.

The recent macroeconomic impacts of the COVID-19-pandemic on GDP has been reflected in the update of scenarios for socioeconomic drivers, that are built on the previous version of the SSPs (Dellink et al., 2017). Also, the drop-in energy demand is reflected in the historic assumptions of models.

The substantial economic depressions in a series of countries like Syria, Venezuela, Afghanistan (and potentially Russia) and their future economic development prospects have not been considered in the current GDP updates.

The ongoing military conflicts, the Russian invasion in Ukraine and the dynamically developing situation in the Middle East, have specific immediate effects on energy and food markets (Liu et al. 2023). The longer-term implications of these events cannot be reasonably projected. Thus, no specific assumptions have been considered for the socioeconomic drivers. In several models, the assumptions about Russia's fossil fuel exports are lowered to reflect the European import ban.

In the context of the Shared Socioeconomic Pathways, the narrative of SSP3 "Regional Rivalries" reflects a future with increasing nationalism, fracturing of international institutions of cooperation and stagnant socioeconomic and sociotechnical development. In such a future the reliance on fossil fuels remains high and concerns regarding energy and food security are crucial for national policies. The development of low-carbon technologies is expected to be slow with huge barriers to change structures. These conditions lead to high challenges for mitigation and adaptation. In the context of ScenarioMIP, the high emission scenario is expected to rely on a SSP3-like narrative of socioeconomic development.

Separately from the ScenarioMIP process, the investigation of climate policies in a fragmented international policy context will gain more interest. In addition to the socioeconomic narrative, the increasing political fragmentation can be reflected in climate policy assumptions. In the ScenarioMIP context such considerations are not reflected as scenario specifications. In future scenario work, the role of fragmented policies should be investigated. This could include one or several climate clubs in which like-minded nations coordinate policies, e.g. cap-and-trade systems, as well as the relationship with third parties. Such fragmented policy regimes can be compared to the globally integrated approaches to better understand the consequences of geopolitical constraints that frame and limit international cooperation.

Moreover, the implications of climate change impacts and mitigation action will have consequences for the overall international security architecture and risks in the international security situation. For example, the phase-out of fossil fuels has implications for energy security for both importers and exporters, also the imposition of energy security policies has implications on energy related CO_2 emissions (Jewell et al. 2016).

For ScenarioMIP, the REMIND-MAgPIE team has implemented a scenario that follows a SSP3 type narrative (Fujimori et al. 2017) that provides the overall socioeconomic narrative for the High scenario in ScenarioMIP. It features low economic growth and long-lasting disparities in income levels across the world. Population growth in low and middle-low income countries remain strong. Despite low GDP growth, emissions increase due to slow technological improvements and a full rollback of existing climate policies. Also, land-use change is intensified and air pollution emissions (i.e. aerosol) are high. In such a future the challenge to adaptation is high and the lack of international cooperation due to (chauvinistic) nationalistic tendencies

remain high. Such a world will be characterized by multiple crisis unfolding in parallel. Although a scenario at the aggregate level that is used in ScenarioMIP does not map out individual crisis, such scenario provides the context in which such crisis is expected to occur frequently and there is only a low capacity to deal with them.

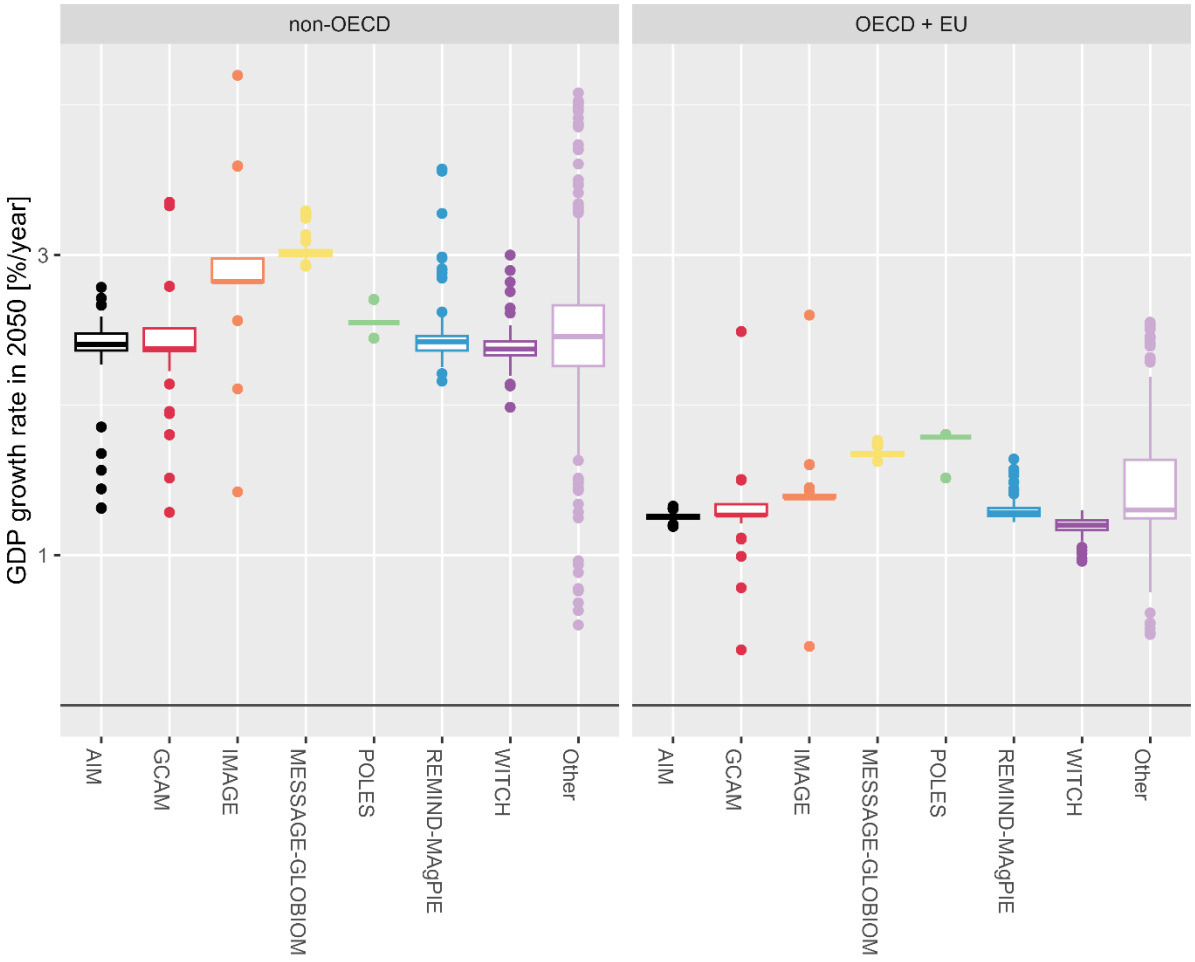
This type of scenarios raises a great number of research questions. The important role of high-quality institutions for both socioeconomic development and conflict resolution and international cooperation are a starting point for interesting and policy relevant research questions.

4.7 Synergies and Trade-Offs between Climate Change Mitigation and Strategies of Degrowth and post-Growth

In recent years the concepts of degrowth and post-growth have gained popularity pushed forward by advocacy groups and researchers. Basically, the main argument is that lower economic growth in developed countries is a pre-condition for effectively reducing global GHG emissions and, more generally, resource use to observe climate and broader environmental guardrails. A major assumption is that a decoupling between economic activity and energy use and emissions is not feasible. When energy efficiency improvements and the decarbonization of the energy sector are assumed to be not feasible, limiting economic activity is the only effective strategy. The argument is extended to welfare and equity issues as well as societal modernization and emancipatory progress. An overview of the literature and the various approaches is provided by Jakob et al. (2020) whereas van den Berg and Botzen (2024) review the methodological foundations identifying substantial scientific quality deficiencies in de-growth literature.

The assumptions about GDP growth in IAM scenarios are usually a combination of extensions of historical growth rates (also relying on IMF (International Monetary Fund) projections) and more long-term narratives of economic growth. The SSP process provided GDP projections derived with a structural model of economic growth that translated the SSP narratives into parameters and derived the future growth projections (Dellink et al. 2017). Generally, all SSPs show continuously increasing per-capita income in all regions with differences in the income convergence of developing countries (mostly non-OECD) to developed countries (mostly OECD member countries). Figure 12 shows the annual growth rates for different models in 2050, which reflects this narrative as well.

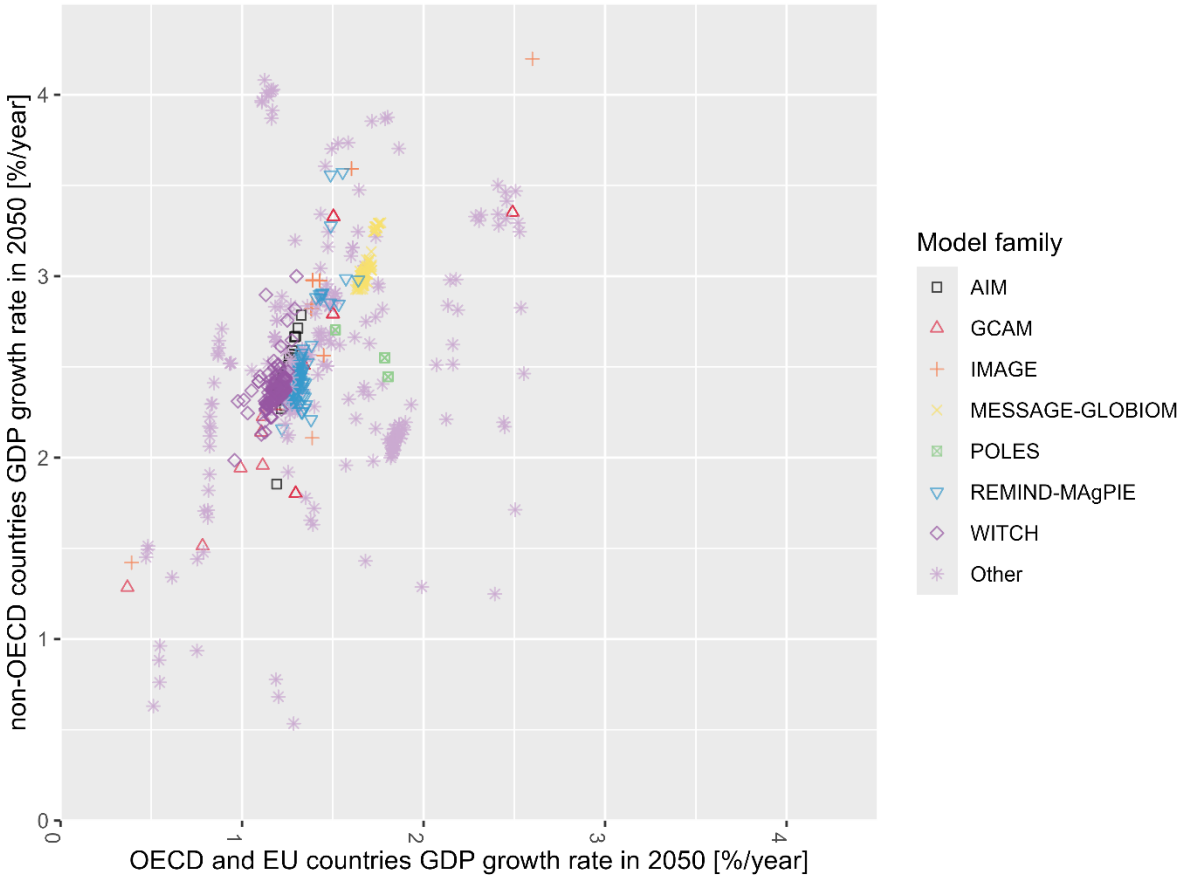
Figure 12: Projected annual economic growth in 2050 across models in the AR6+ database for non-OECD and OECD countries



Source: AR6+ database.

In the context of the SSPs and the consecutive IAM literature the critique pointed at the SSP1 that represented a sustainable development narrative, but did not represent the de-growth narrative of stagnating incomes in developed countries. A review of the AR6+ database shows that in fact no scenario combined low growth in developed countries with high growth in developing countries. In Figure 13 de-growth scenarios would be located in the upper left part of the scatterplot, which is however not populated by scenarios.

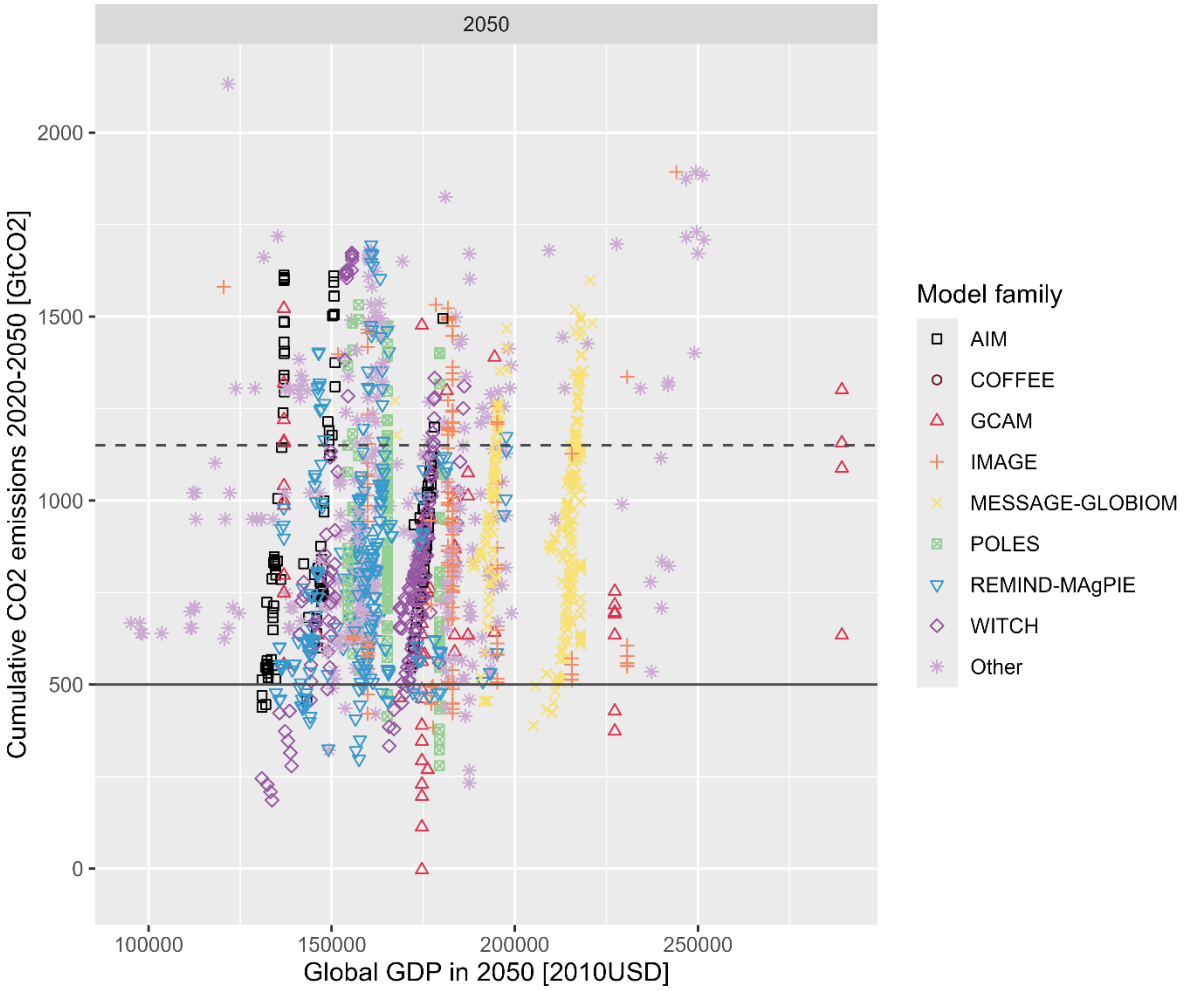
Figure 13: Scatterplot for the annual growth rates in 2050 for OECD and non-OECD in scenarios of the AR6+ database



Source AR6+ database.

The AR6+ database also does not show any clear interaction between growth and cumulative emissions as it is shown in Figure 14. Actually, high and low emission scenarios are shown at all levels of global 2050 GDP. Thus, across all IAMs the representation of a post-growth scenario would very likely not provide any novel results regarding the feasibility of low emissions. Thus, the decoupling of emissions and economic activity is achievable in the context of the existing IAM models and replacing fossil fuels by renewable energy technologies the most important way to lower emissions. Actually, the fundamental finding is that climate change mitigation and achieving the 1.5°C does not undermine economic development. Moreover, in the context of the ScenarioMIP process it is expected that the high emission scenario will follow a low-growth SSP3 narrative of regional rivalries (see above). This will be a major difference to the 2017 edition of the SSPs, in which the high emission scenario actually followed a high-growth SSP5 type of scenario (Kriegler et al. 2017). However, progress in non-fossil technologies and electrification make it unlikely that high growth scenarios will still lead to emissions that strongly increase over the course of the 21st century.

Figure 14: Scatterplot of cumulative global CO_2 emissions 2020-50 against the global GDP level in 2050 for various IAM models and scenarios from the AR6+ database



Source: AR6+ database.

A single study has introduced this combination of climate change mitigation and de-growth pathways (Keyßer and Lenzen, 2021). However, no economic reasoning and no empirical backing is provided by the authors. In a recent study Soergel et al. 2024 examine a post-growth scenario with slightly increasing per-capita incomes in developed countries, while still assuming moderate growth in developing regions and compare it with scenarios that follow different sustainability-oriented narratives. Soergel et al. (2024) note that a post-growth scenario may lead to reduced reliance on CDR and may also show improved performance regarding bio-diversity losses. Regarding these two important issues the future development of dietary choices and land-use management is found to be crucial (Humpenöder et al. 2024a); thus, the performance on these objectives does not necessarily depend on the level of GDP. Also, stronger income convergence would lead to even stronger growth of food demand compromising the land-related environmental objectives (Bodirsky et al. 2022).

So far, the theoretical foundation of de-growth and post-growth scenarios is not well-developed. The slowing of economic growth could have many different reasons and thus very different consequences for the use of natural resources and the ability to induce reductions of resource use and emissions by means of policies. A thorough scientific investigation of these issues is necessary to properly understand economic systems that slow down economic growth. So far, the main line of investigation only considers a slow-down of exogenous assumptions of

economic growth without asking for the underlying reasons and how these interact with the resource use and investigating sensitivity with respect to targeted policies.

Proponents of de-growth argue that degrowth promotes civil liberties and emancipation. Economic literature points out that promoting societal objectives of emancipation, civil liberties and leveling the playing field for example on the labor market would increase economic growth. For example, Hsieh et al. (2019) argue that progress in the removing of privileges in the US society after WW2 lead to a larger participation of women and non-white Americans in the labor market. It was found that between 1960 and 2010 between 20% and 40% of economic growth is due to the improved allocation of talent in the US labor market. Thus, the mean of slowing down economic growth could be in a fundamental contradiction with objectives associated with de-growth strategies. Emancipatory modernization of societies and legal frameworks in developed countries could increase economic growth.

4.8 Synergies and Trade-offs between Climate Action and other Sustainable Development Goals

Climate change has a central role within the SDG agenda. Not only its impacts can affect progress towards achieving most of the SDGs. Also, the adaptation and more importantly the solutions to it interact with the other SDGs in a myriad of ways (Fuso-Nerini et al. 2019).

To mention a few examples, naive implementations of carbon pricing can be substantially income-regressive at the regional, country and household levels (Feindt et al. 2021, Soergel et al. 2021a). Also, as will be discussed in more detail in Section 4.11, land-based solutions to climate change such as afforestation or the use of bioenergy directly affect land-use and are also constrained by the broader context set by the agricultural and forestry sectors as well as the regulations of land-use (Fuso-Nerini et al. 2019, Soergel et al. 2021b, Humpenöder et al., 2022). The knock-on impacts on food production and markets have consequences both to the more biophysical aspects of the SDGs through water use, fertilizer pollution and land conversion and degradation (SDGs 6, 14 and 15), and to the socioeconomic aspects through changes in food prices and access, labor markets and power structures (SDGs 1, 2, 3, 8, 16, and 17).

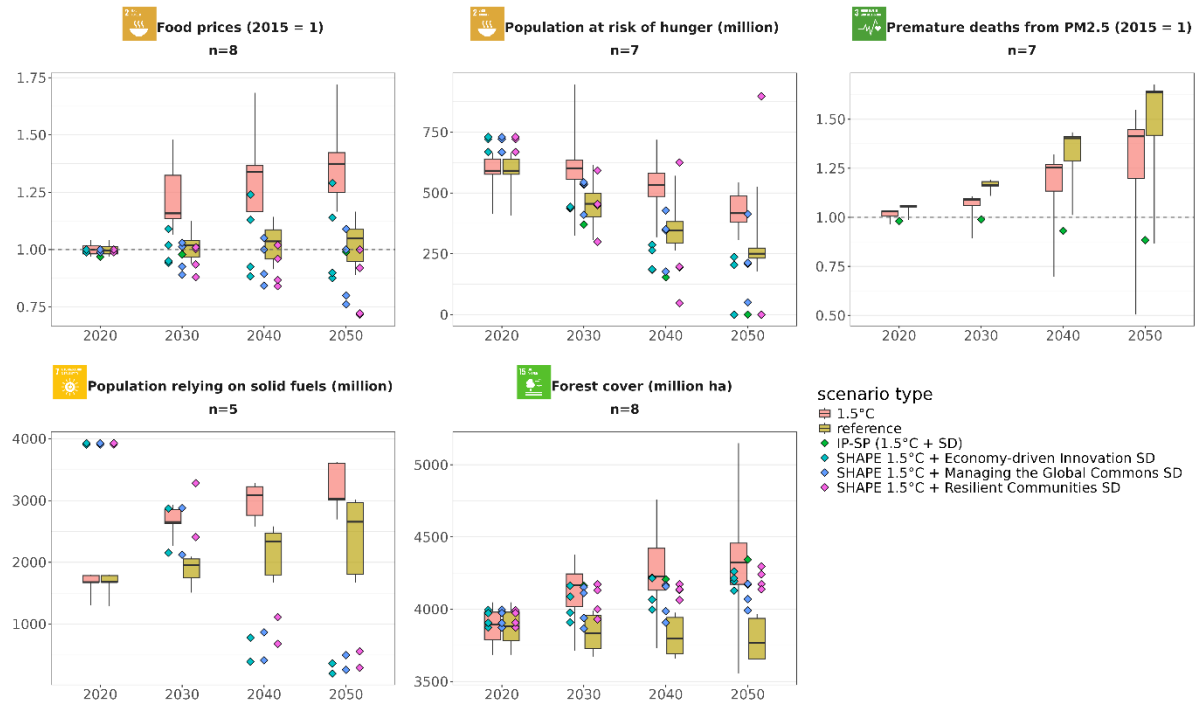
Integrated Assessment Models can be a powerful tool to investigate many of these SDG interactions of climate action, and IAMs such as REMIND-MAgPIE are especially well-positioned to inform the climate policy debate about such interactions (Van Vuuren et al., 2016, van Soest et al., 2019, Soergel et al. 2021b). Several works use IAMs to show how adjustments to naive climate policy design can avoid tradeoffs and leverage synergies with other SDGs, usually covering interactions related to energy and food prices, forest or biodiversity loss and air quality (Bertram et al., 2018, Fujimori et al., 2020, Humpenöder et al., 2022a, Merfort et al. 2023a). However, most IAMs come from a primary focus on climate policy, and covering other SDGs often requires additional effort in the scenario building and communication process. At a methodological level, this extra effort ranges from tweaking and expanding the modeling approaches of IAMs with additional sub-models and assumptions to sometimes simply analyzing variables that are computed by the model but are usually ignored in scenario assessments.

The AR6 WG3 included a dedicated subsection on mitigation and sustainable development and large part of Section D of the SPM was dedicated to the topic. The assessment relied on the analysis of the outcomes of IAM-derived mitigation pathways in terms of other SDGs. The analysis highlighted how very few IAM scenarios in the AR6 database contained useful information on other SDGs beyond climate (Figure 15). Data on 5 indicators relevant to SDGs 2, 3, 7 and 15 showed that narrow-focused mitigation pathways generally tend to worsen the outcomes for food prices, population at risk of hunger, reliance on solid fuels and forest cover,

although they show some health co-benefits by reducing air pollution. The limited breadth of submissions reporting the SDG-relevant variables implies that the uncertainties only cover a smaller range than what would be expected for a larger compliance of reporting. The limitations in reporting are related to the gaps in modeling the full suite of implications of transformation pathways on SDG relevant indicators.

Figure 15: Effect of climate change mitigation on different dimensions of sustainable development: shown are mitigation scenarios compatible with the 1.5°C target (red) and their respective reference scenarios (yellow)

Red box plots contain AR6 scenarios that include narrow mitigation policies from different studies. This is compared to four different scenarios differentiated by the colored diamonds. The sustainable development AR6 marker scenario (IP-SP, Soergel et al. 2021b) integrating mitigation and SD policies (e.g., zero hunger in 2050 by assumption) and three scenarios from the SHAPE project that include different assumptions toward sustainable development (Soergel et al. 2024). Figure adapted from AR6 WGIII Fig3.38 (Riahi et al. 2022), courtesy of Bjoern Soergel.



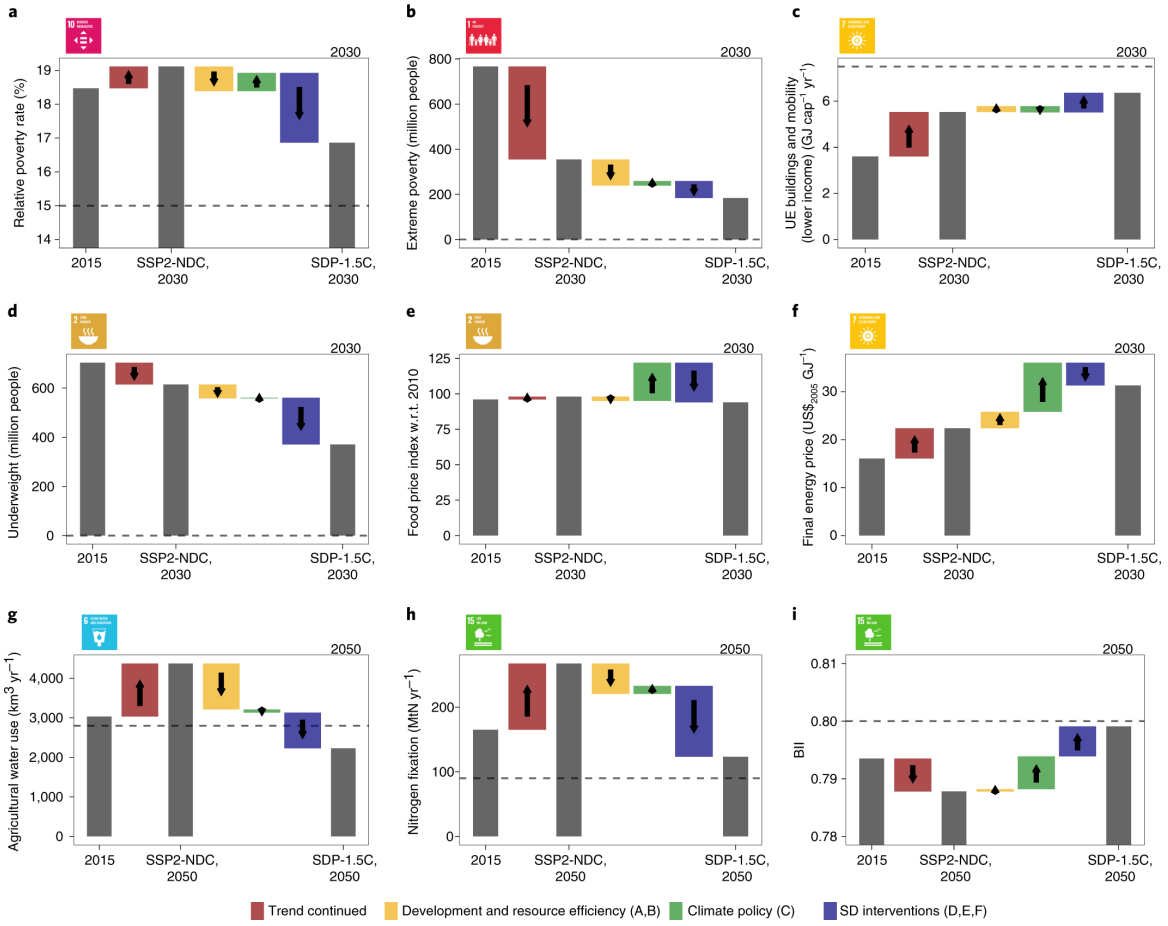
Source: see caption. License: CC BY 4.0.

Only one study in the AR6 database addresses indicators of all 17 SDGs (Soergel et al. 2021b), including a scenario that assumes targeted and holistic sustainable development measures (the illustrative pathway IP-SP in Figure 16). It highlights that interventions targeted to address SDGs other than climate can have synergies with climate policy and alleviate its tradeoffs, with the potential to achieve or get very close to achieving all SDGs by 2050 if not 2030.

However, a single scenario of a single model is far from representing the diversity of points of view and modeling approaches in the climate science community, let alone all the scientific communities that contribute to SDG knowledge. To properly inform stakeholders on climate policy design that recognizes and addresses SDG interactions, advancements on different fronts would be crucial.

Figure 16: Combined effects of climate policy, human development and resource efficiency and targeted sustainable development interventions on SDG indicators in a mitigation scenario

a, Relative poverty rate. b, Extreme poverty. c, useable energy (UE) buildings and mobility (lower-income). d, Underweight. e, Food price index. f, Final energy price. g, Agricultural water use. h, Nitrogen fixation. i, Biodiversity intactness index (BII). The first step in dark red denotes the trend from 2015 to 2030 (or 2050) assuming no major break with recent historical trends and the implementation of current NDCs (SSP2-NDC). The second step illustrates the shift to a pathway with more rapid development, higher resource efficiency and more environmentally conscious lifestyles (SSP1-NDC, yellow), while the third step shows the addition of an ambitious, Paris-compliant climate policy (SSP1-1.5C, green). The final step, representing the major innovation of this paper, illustrates the added value of additional sustainable development interventions in the domains of inequality and poverty, nutrition and energy access, as well as additional energy and land-use policies (SDP-1.5C, blue). The first two rows of indicators show SDG-related outcomes in 2030; the final row relates to planetary boundaries in 2050. Target values for 2030 (2050) are indicated by the dashed lines. Source: Soergel et al. 2021b

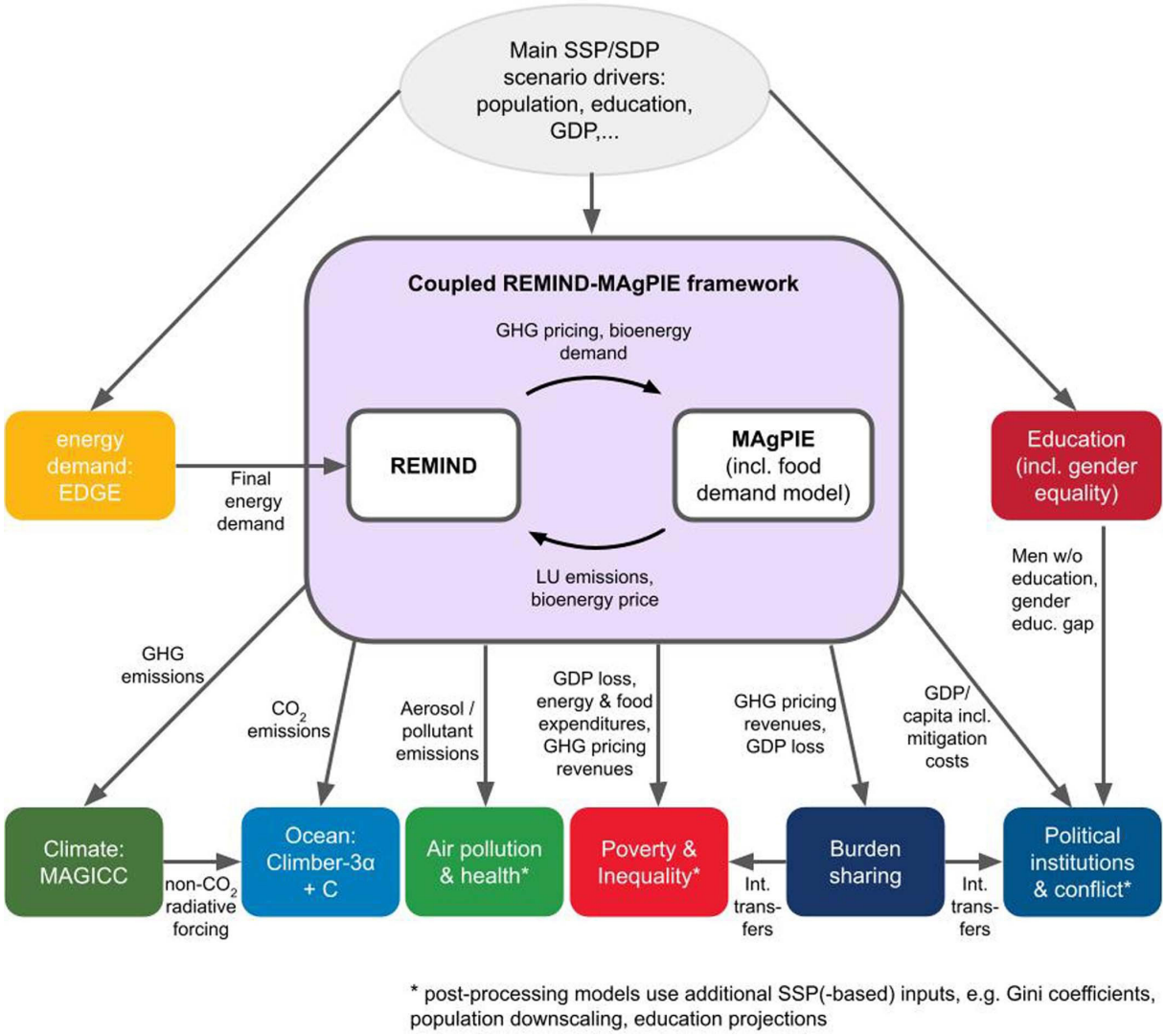


Source: See caption. License: CC BY 4.0.

First, addressing other SDGs in IAMs requires integrating them with many modeling tools from different disciplines (see for example the Soergel et al. 2021b modeling framework in Figure 17). This kind of integration is still in its infancy, allowing for just a minimal set of indicators and missing many SDG linkages identified in the literature, especially those pertaining to the social sciences. For example, interactions between education, poverty, gender equality and demography are still challenging to model. But also, interactions more recently identified in the biophysical realm, such as the consequences of the deployment of novel CDR technologies such as ocean alkalinity enhancement on natural ecosystems are yet to be assessed in a consistent scenario framework.

Evaluating other SDGs within IAM scenarios also requires huge collaboration efforts between modeling teams of different disciplines. Building more robust tools and interlinkages that can simplify and streamline the process is crucial for reducing the barriers of entry and enable a holistic SDG coverage and focus into specific SDGs and the various indicators on more scenarios by more modeling teams.

Figure 17: Modeling framework used to evaluate SDG indicators in Soergel et al. 2021b



Source: Soergel et al. 2021b. License: CC BY 4.0.

Finally, including more SDGs in IAM assessments increases the dimensionality of the results. To properly investigate this space the scenario designs must be broadened which results in a greater scenario diversity. The investigation of this broader set of scenarios will require additional expertise. There are many different perspectives on how to achieve the SDG agenda and the Paris Agreement goals, ranging from focusing on global economic and technological development to post-growth perspectives that focus more on strengthening communities. Assessing the consequences of these different perspectives in a way that is useful for policy makers requires new and diverse modeling approaches across different scales. One promising EU project, SHAPE (https://shape-project.org/), aims to address some of these challenges with a stakeholder-driven scenario generation process and collaboration between a limited set of IAM

teams, but much improvement in granularity is still needed to properly inform debates at a country or state level.

IAMs are appropriate tools to investigate the synergies and trade-offs between climate change mitigation strategies and other relevant public policy targets in the SDG context. To improve the structural interactions between these systems and the corresponding SDG indicators improvements in the IAM frameworks would be valuable. For the identification of solution strategies for policies the following lines of arguments could be considered.

In general, reductions in the demand for resource intensive goods and services, be it for industrial materials or for food products (specially ruminant meat), although not sufficient to achieve ambitious climate targets by themselves, can substantially ease the burden of other mitigation strategies, making these targets achievable with lower prices for energy, food and GHG emissions, minimizing tradeoffs with other SDGs and creating substantial co-benefits with them (e.g. Humpenöder et al. 2024). In particular, scenarios that do not include measures to reduce energy demand generally require substantial amounts of Carbon Dioxide Removal (CDR), which depending on the technology used can have important impacts on land systems and ultimately on land biodiversity and food availability (Humpenoder et al. 2022a, Riahi et al. 2022).

Among demand reduction measures, fostering more sustainable and healthy diets and reducing food waste greatly facilitates transformations towards sustainability that also addresses human well-being and development and leads to particularly beneficial impacts across many SDGs with little side effects. They have a synergistic effect with climate mitigation and land and biodiversity protection measures, as reduced demand for food frees more land to be used for mitigation and conservation. This land-sparing effect also counteracts potential increases in food and land prices from climate mitigation and land protection policies. Proposed shifts in human diets can also have substantial benefits for human health, reducing health issues related to obesity and facilitating the reduction of different types of hunger (Willett et al., 2019, Bodirsky et al. 2020, Humpenoder et al. 2022a, b).

4.9 Fairness, Equity and Justice Arguments in Climate Change Mitigation Pathways

Equity, justice and fairness as well as cost-effectiveness are key policy criteria in the Paris Agreement. In the IAM community these issues are related to broad set of modeling approaches, scenario assumptions and outcomes. A major argument is the question about the differentiation of carbon prices and the use of financial transfers to compensate countries that are hit harder and bear a greater economic effort than others, but can also reduce emissions by relatively large quantities. The arguments about fairness, equity and justice are mostly discussed in the context of potentially adverse distributional effects of emission mitigation policies and how to manage them. This needs to be distinguished from SDG such as the eradication of poverty (SDG1) and the achievement of economic growth (SDG 8), which are aiming at absolute socioeconomic conditions and equity. In the context of climate policy, particularly emission mitigation policies, the concerns are about adverse socioeconomic effects resulting from the attempt to reduce emissions. Thus, climate policies and equity are analyzed with respect to their distributional effects and how distributional conflicts could be resolved in an equitable manner. Thus, achieving an SDG, like the eradication of poverty or the access to clean energy can be seen as an important objective that should not be undermined by climate policies. The perspective is not to solve overall distributional issues like global income inequality by means of climate policies.

The calls for equity and fairness in climate policies are justified as cost effective policies lead to regressive income effects as poorer countries and poorer households spend a higher share of incomes to satisfy basic needs such as energy and food and are also more constrained to invest in low emission technologies as income levels are low, capital is scarce and low-emission energy technologies have higher shares of capital costs. Financial transfers can neutralize the unequal impacts, but the financial volumes are considerable and would very likely be outside the political feasibility.

This comes with the notion of common-but-differentiated-responsibility-and-respective-capabilities (CBDRRC). This notion asks all nation states to reduce emissions, which is different to the Kyoto-Protocol that differentiated developed and industrialized countries (Annex 1 countries) that have agreed to accept commitments of emission limitations under the UNFCCC. The Paris Agreement broadened the basis to all countries to pledge Nationally Determined Contributions (NDCs). At the same time all countries are committed to the process of Global Stocktake and ratcheting-up of NDCs with 5-year cycles.

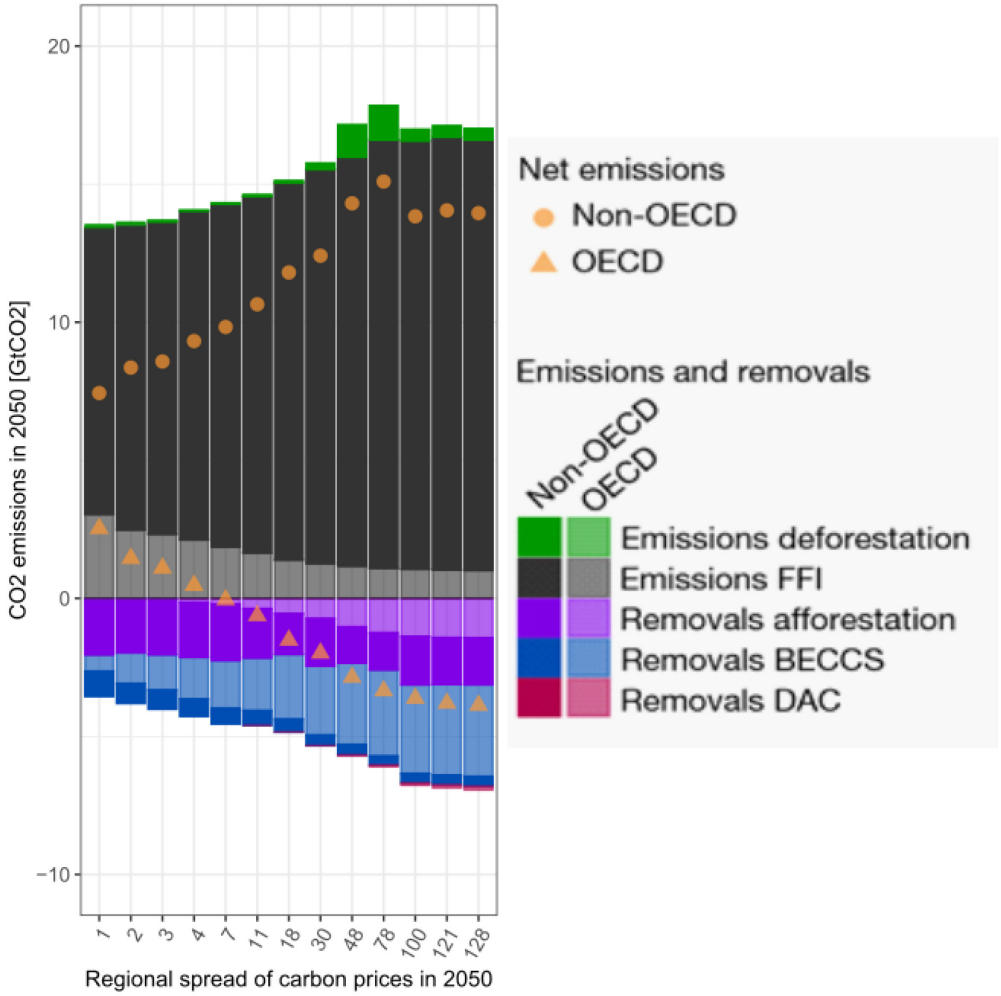
The scenarios that the IPCC reviews and that are collected in the AR6 database are mostly derived under the policy assumption of uniform carbon prices across regions. This policy assumption is justified as it implies cost-effective implementation of the global emission reduction requirements. However, from a fairness perspective it would require substantial financial transfers in order to avoid regressive income effects. In turn these transfers are difficult to negotiate as nation states typically insist on their fiscal sovereignty. At the same time, it is known that international agreements are frequently not effective, if there is no general economic or even specific fiscal advantage for the parties/countries involved. This is the case for international environmental agreements such as the Paris Agreement in particular. The three-dimensional trade-off between efficiency, equity and fiscal sovereignty has been analyzed by Bauer et al. (2020). More analysis on the effect of differentiated carbon prices can be found in Chateau et al. (2023). The studies by Soergel et al. (2021a,b) applied a scheme of moderately differentiated carbon prices, but did not study the impact systematically. A more general treatment on the differentiation of price policies has been provided by Stiglitz (2019).

The preliminary protocol for ScenarioMIP has highlighted the importance of equity principles for the climate change mitigation scenarios, but the specifications have not been clarified yet. The specifications of a pattern for differentiation are challenging from a purely scientific perspective because alternative equity and fairness principles can be applied and the degree of differentiation can be varied. For example, Bauer et al. (2020) varied the degree of carbon price variations up to a factor of 128 between the lowest and the highest carbon price and maintaining this spread over the 21st century, while still the same carbon budget and same fairness criterion was achieved by filling the residual equity gap with financial transfers.

Bauer et al. (2020) found that the transformation pathways are sensitive to the carbon price differentiation (see Figure 18). Countries with low carbon prices are less willing to transition and deploy CDR, whereas the use of fossil fuels was extended. High price countries accelerated the transition, phased out fossil fuels quicker and deployed more CDR. At the global level it turned out that gross fossil fuel and industry as well as Land-Use Change (LUC) CO_2 emissions increased, which was off-set by more CDR. The overshoot increases. Moreover, bio-energy was grown in low-price countries causing deforestation and shipped to high price countries to facilitate BECCS.

Figure 18: CO_2 emissions and removals differentiated by sector and region in 2050 consistent with the wb-2K target for varying carbon price differentiations across regions

The regional spread of carbon prices measures the ratio between the highest and the lowest carbon price. A spread factor of 1 (left hand side) represents uniform carbon pricing while the highest spread factor of 128 is required so that all regions experience the same relative income loss. For the intermediate cases the degree of carbon price differentiation decreases. The total global net CO_2 emissions are around 10 $GtCO_2$ per year with only little variation.



Source: Based on Bauer et al. (2020).

In order to better understand the consequences of carbon price differentiation a broader sensitivity analysis would be useful. To constrain the space of policy differentiation stakeholder interactions could help to prioritize alternative formulations. In turn, the outcomes of such variations and the resulting market distortions, e.g. bioenergy and food markets, would be interesting to better evaluate the environmental impacts and the impact on the overshoot magnitude and duration. Such analysis would help to better understand the synergies and trade-offs between socioeconomic equity and environmental sustainability.

The ScenarioMIP group plans to consider carbon price differentiation with a perspective on equity, fairness and justice, but also regarding short-term feasibility constraints for the evaluation of scenarios. However, there will not be a systematic comparison of the effects within the ScenarioMIP process. That would require a harmonized scenario protocol with multiple scenarios. For instance, a set of carbon price differentiation patterns would be investigated that vary the level and spread factor of carbon prices, the convergence patterns and the

differentiation scheme that could be guided by per-capita income, historic emissions, etc. pp. These vastly different carbon price patterns will be imposed on the models subject to the same long-term climate change targets of the ambitious mitigation scenarios. The analysis will investigate the regional and global transformation pathways and emissions. A major question will be to which degree the differentiation will lead to intertemporal and international reallocation of emissions. For instance, a larger spread of carbon prices could lead to a higher temporary overshoot driven by low-price countries. Alternatively, the differentiation could also lead to small changes in global emissions but huge reallocation between countries. ScenarioMIP can only investigate the consequences of such model responses. The difficulty is to cover a broad spectrum so that very different political positions are covered and the consequences of the choices are made as transparent as possible.

The analysis of differentiated carbon prices, however, is subject to a crucial assumption: the global total of all emissions is set and only open question is how to fairly distribute the burden. This is structurally similar to the issue of allocating emission permits following some fairness criterion. Although these are reasonable research questions, they are relatively far away from the actual political negotiations and, therefore, national governments are difficult to convince. A different approach is to use an IAM with integrated impacts of climate change on GDP and other relevant variables. In such a model context the adverse impacts would constitute the nations/regions willingness to pay to avoid global climate change. The assumptions about scenarios can then vary the way how governments could express and realize their willingness to avoid climate change by domestic mitigation as well as cooperation and collective action. In this context the global total of emissions is derived endogenously. This is the idea of Lindahl solutions to public good provisions and has been mentioned in Chapter 2. It has also been mentioned that this theoretically appealing approach has not been applied in the context of process-based IAMs as of today.

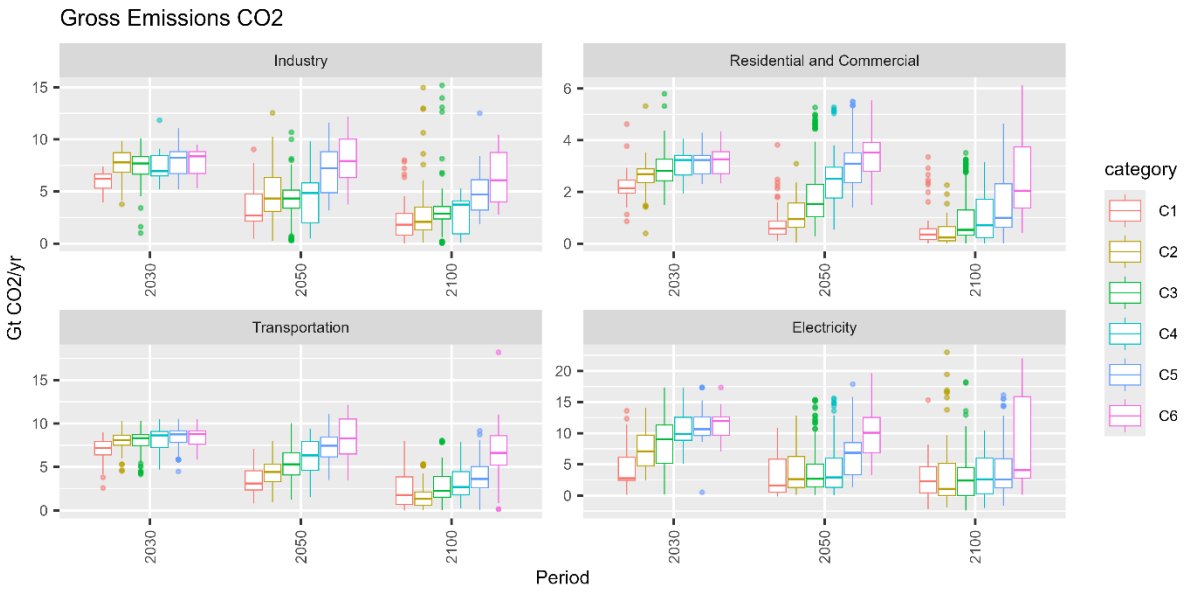
4.10 Sectoral and Regional Residual Emissions from Fossil Fuels

The use of fossil fuels is, as of today, by far the largest contributor to climate change. Without substantial climate policies to reduce GHG emissions this would continue throughout the 21st century (McGlade and Ekins 2015, Riahi et al. 2017, Bauer et al. 2016a, Bauer et al. 2017). In the First Global Stocktake governments agreed to phase-down fossil fuel use.

The imposition of strong climate policies will lower the use of fossil fuels and incentivize carbon capture and sequestration, but a residual use of unabated fossil fuels and corresponding emissions might remain (Luderer et al. 2018). As long as positive net CO_2 emissions are permissible and/or carbon removals offset gross CO_2 emissions, residual emissions are consistent with a given climate objective. A major question is in which regions and sectors these residual emissions occur. It is reasonable to understand in which sectors and regions the use of fossil fuels could still continue and given the uncertainties about the climate system and the potential need to reduce CO_2 emissions. Once the sources of residual emissions are understood in a next step it can be asked which technologies and policies may be required for additional reduction of fossil fuel use to address the uncertainties.

Figure 19 shows the gross emissions from residual fossil fuel use for the sectors electricity supply, industry, transport and residential & commercial. The medians across models show substantial residual emissions across all scenarios by 2050, but also in 2100. The Electricity sector is the most responsive due to the possibility to substitute fossil fuels with renewables (and also nuclear) or to abate CO_2 emissions by means of CCS.

Figure 19: Residual gross CO_2 emissions differentiated by sector and IPCC climate target category



Source based on AR6+ database.

For the 1.5°C compatible scenarios C1 and C2 there is interesting pattern. Across sectors the residual emissions are higher in 2050 if the overshoot is allowed (case C2), whereas in 2100 the ranking is reversed and the case C1 with no or low overshoot shows higher emissions. This follows the pattern of the carbon prices discussed above. The lower carbon price in the second half of the century in C1 scenarios allows higher residual emissions as the carbon removals serve as offsets to stabilize the global mean temperature.

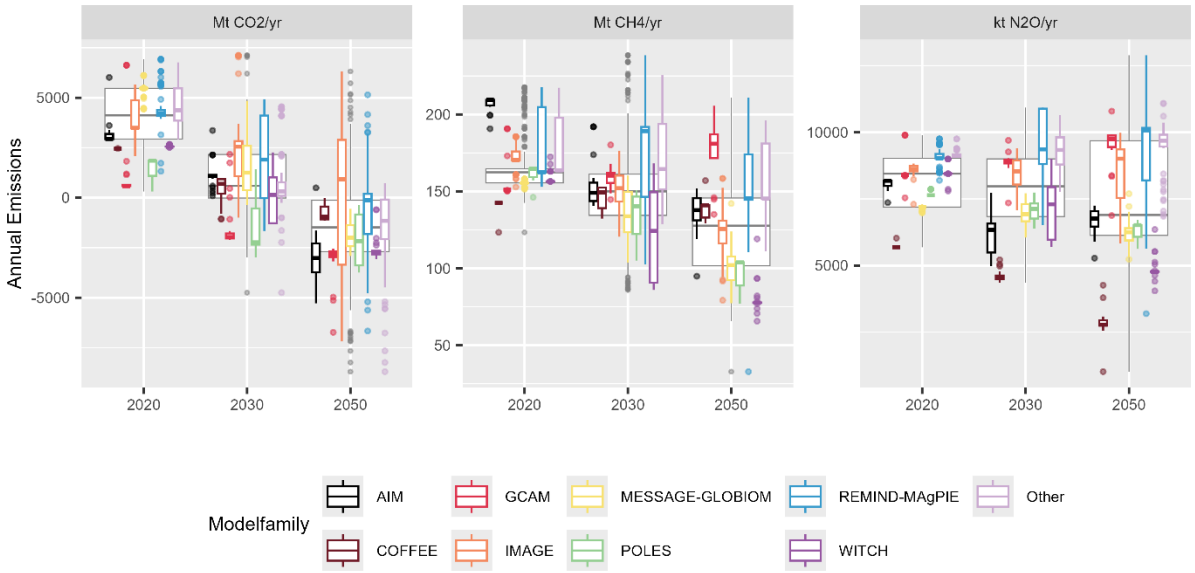
Interestingly the uncertainty ranges depicted by the whiskers do not show clear patterns. The ranges for the C1 and C2 cases vary across sectors and time. This is surprising because it would have been reasonable that the C1 scenarios with low or no overshoot are more constrained and therefore reduce the uncertainties to larger degree than the C2 scenarios that allow more flexibility.

4.11 Integration of Land-use Policies into Climate Policies

A substantial share of greenhouse gas emissions is caused by the Agriculture, Forestry and Other Land Use (AFOLU) sector. Land-use change (LUC) CO_2 emissions contribute with ca. 9.4% and AFOLU-based CH_4 and N_2O emissions with 10.1% to total GHG emissions in CO_2-eq today (Lamb et al. 2021). These emissions are subject to large uncertainty and also the contribution to climate change mitigation differs strongly between scenarios (see Figure 20 showing AFOLU emissions in C1, C2 and C3 scenarios).

Figure 20: AFOLU emissions of AR6 C1, C2 and C3 scenarios

a) Annual CO_2 emissions, b) annual CH_4 emissions and c) annual N_2O emissions. Emissions are grouped by model. All models that are not stated individually are grouped to "Other". The grey boxplot in the background summarizes all scenarios, irrespective of the model. Please note that a few outliers were removed by excluding CO_2 emissions below -10 000 Mt/yr, CH_4 above 2000 Mt CH_4/yr and N_2O emissions below 10 kt N_2O/yr for better clarity. We believe the outliers are due to reporting issues that were not filtered from the original data base.



Source: own compilation based on AR6+ database.

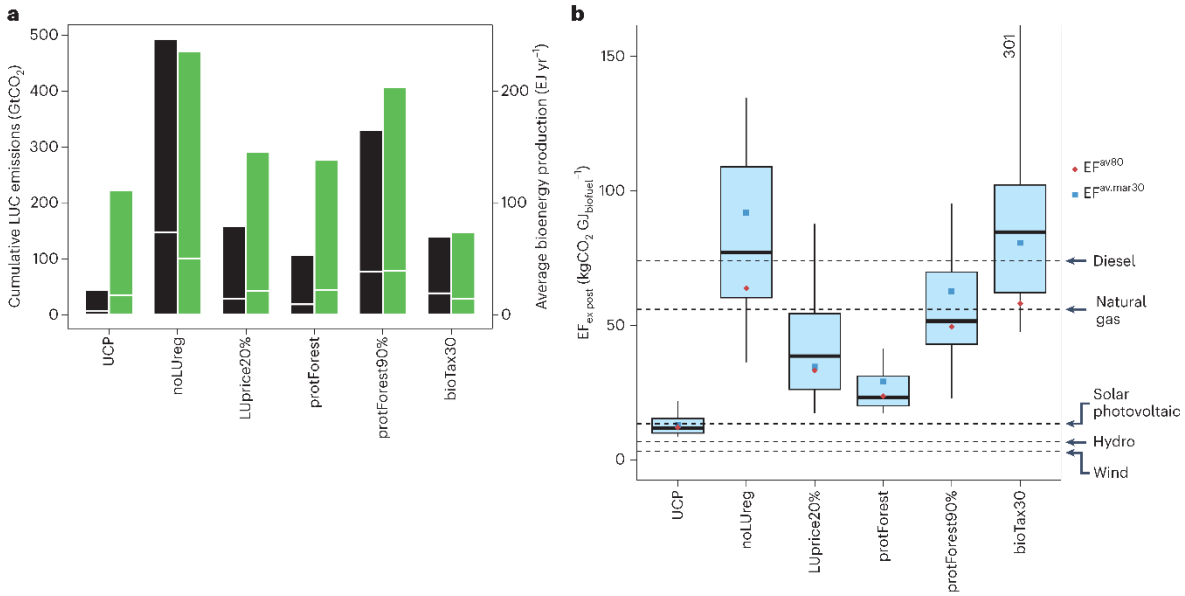
In IAM scenarios land-use policies are often idealized with either a price on land-based CO_2 emissions or with explicit nature conservation schemes to effectively prevent emissions from LUC in the models. With such a pricing of land-use related GHG emissions net AFOLU CO_2 emissions drop, on a median, from over 4,000 Mt CO_2 in 2020 below 600 Mt CO_2 already by 2030 and turn largely negative in most scenarios by 2050. Given that this is not in line with currently implemented - let alone enforced - land-use policies, emissions reductions may be overestimated. Thus, higher land-use emissions would reduce the remaining carbon budget from the energy sector. This is particularly problematic in combination with the high demand for bioenergy due to demand caused by rapid decarbonization requirements, which is projected to increase substantially in ambitious climate change mitigation scenarios. If bioenergy demand and the corresponding willingness to pay for energy carriers hits a largely unregulated land-sector, LUC emissions can be massive and strongly jeopardize its mitigation potential (Merfort et al. 2023a, see Figure 21, reproduced from Merfort et al. 2023b), resulting in an average emission factor from biofuels that may be, on a unit basis, similar to the combustion emissions from diesel fuel.

Compared to CO_2, AFOLU-based CH_4 and N_2O emissions reductions are not as large on an absolute basis (CH_4 decreases from 162 to 150 Mt CH_4 until 2030 (8%) and N_2O from 8440 to 7970 kt N_2O (6%)). Yet, given that population is still growing and that some growing economies are in the process of catching up to developed countries with their consumption of animal-based products, even these small reductions – typically induced by GHG prices on these non-CO_2 GHG – may be overestimated. Rogelj and Lamboll et al. (2024) find that the CO_2 budgets, which are implicitly derived assuming these reductions, will be substantially smaller under less optimistic assumption, "putting the achievement of the Paris Agreement out of reach".

While IAM scenarios with effective and comprehensive land-use policies (e.g. uniform GHG prices) are important to set the benchmark solutions (to analyze what is theoretically feasible), it is of great importance to also give policy guidance in an environment that considers policy failures in the AFOLU sector, imperfect institutions, societal barriers to change or myopic actors. Here the IAM literature is rather thin, calling for more scenarios that explore the space of an "imperfect policy" environment. There is a lack of understanding (or at least a lack of knowledge transfer from social and political sciences to IAMs) about what barriers hamper effective and globally comprehensive AFOLU policies and how they could be overcome, which calls for more interdisciplinary research to inform IAMs. Eventually, the uncertainty regarding AFOLU CO_2 emissions needs to be reduced and the inconsistencies across models and national inventories (Grassi et al. 2023) needs to be tackled in order to provide more targeted policy recommendations.

Figure 21: Bioenergy-induced land-use change emissions, bioenergy production and biofuel emission factors in future climate change mitigation scenarios

In panel a) Bioenergy-induced land-use change emissions (black bars) are contrasted to bioenergy production (green). The scenarios differ with respect to assumptions to land-use and energy policies. In the absence of land-use regulations (noLUreg), bioenergy-induced LUC emissions are increasing tenfold compared to the scenario with uniform carbon prices (in the UCP scenario LUC CO_2 emissions are penalized with the same carbon price as the carbon price on fossil emissions). Accordingly, the bioenergy emission factor (EF) per unit of bioenergy produced (panel b)), increases and also taxing bioenergy that dampens the demand (bioTax30 scenario) is incapable do reduce these average emissions from biofuels – only globally comprehensive land-use policies are effectively reducing the EF.



Scenario	Land-use (LU) sector policies	Energy sector policies
UCP	Uniform carbon price (UCP) on all greenhouse gases at energy sector level	Bioenergy is treated as carbon neutral
noLUreg	No LU regulatory policies	Bioenergy is treated as carbon neutral
LUprice20%	UCP at 20% of the energy sector level on all greenhouse gases	Bioenergy is treated as carbon neutral
protForest	100% of all forests are protected	Bioenergy is treated as carbon neutral
protForest90%	90% of all forests are protected	Bioenergy is treated as carbon neutral
bioTax30	No LU regulatory policies	Carbon price on bioenergy at the level of fossil diesel

Source: Reproduced from Merfort et al. 2023b "State of global land regulation inadequate to control biofuel land-use-change emissions"; https://doi.org/10.1038/s41558-023-01711-7.

The regulation of land-use emissions is very difficult to achieve. The policy process is very far behind in the land-use sector as compared with the energy sector. This can lead to very severe consequences because the decarbonization of the energy sector drives the demand for bioenergy. Bioenergy can be very competitive for the supply of hydrocarbons (oil and gas). Synthetic hydrocarbons as well as green hydrogen and electricity will face a competitive disadvantage, if bioenergy production can be increased without regulations of the corresponding GHG emissions. The resulting expansion of crop-land into unmanaged forests and pastures is also a threat to biodiversity.

As mentioned above the very tricky challenge is to get comprehensive coverage in land-use regulations to avoid loopholes. Thus, it is important to identify and quantify key local benefits for land-use regulations and how global carbon markets can help to bring them into effect. In this context policy analysis frameworks may also include substantial trade restrictions not only including bioenergy, but also agricultural and forestry products.

4.12 Interfaces between Integrated Assessment and Earth System Models

In the sixth assessment report of the IPCC (AR6), the earth system feedback to anthropogenic emissions was derived by Earth System Models (ESM) that operated mostly in "concentration driven mode". This means that the IAM-derived emission pathways of CO_2 and other GHGs where translated via the reduced complexity model MAGICC (Meinshausen et al. 2011) into GHG concentrations and eventually to radiative forcing levels, which could then be used as an input to the medium fidelity and large-scale ESMs (Gidden et al. 2019). Hence, interactive carbon, methane, and nitrogen cycles were not utilized to the full extent possible.[15] Given that the representation of the carbon cycle is one of the largest sources of uncertainty, ESMs now strive to be run fully in "emissions driven mode", directly taking up the emission pathways without the in-between step of calculating concentrations and radiative forcing with MAGICC.

One of the key novelties in that regard is the endogenous representation of CDR within the ESMs. The general idea is to split CO_2 emissions from the IAMs into gross positive and different types of negative emissions, such that the ESMs only use the gross positive emissions as drivers, while the negative emissions from CDR are modeled endogenously. As a consequence, IAMs and ESMs will then overlap in their modeling scopes, since both compute the carbon flows of the different CDR options individually (e.g. BECCS, DACCS, Afforestation, Enhanced Weathering (EW), Ocean Alkalinity Enhancement). This requires a careful design of interface variables to ensure consistency. CDR drivers that need to be transferred to ESMs differ between the CDR options. For BECCS bioenergy crop area needs to be supplied as gridded data, which requires downscaling and harmonization to historical data (CEDS, Community Emissions Data Set, Hoesly et al. 2019) of the often regional IAM output. A challenge in harmonizing IAMs and ESMs is the fact that IAMs typically make assumptions on yield improvements, which the Dynamic Global Vegetation Models (DGVM) within the ESMs do not consider. How these assumptions can be harmonized still needs to be figured out. Additionally, IAMs usually determine the share of biomass that is combined with carbon capture and storage endogenously. This ratio, which may vary in time and can differ between regions, also needs to be passed to the ESMs to compute the amount of CO_2 that is effectively removed from the atmosphere. For more novel CDR technologies such as EW or OAE drivers that need to be passed to ESMs would be a spatial map of ground rock distributed to the fields and a spatial map of e.g. quicklime or alkalinity levels

[15] The term *interactive models* basically means that models are fully coupled and run in an integrated mode considering relevant feedback. Not interactive basically means that the coupling mechanisms are not considered and therefore not all feedbacks are considered.

added to the ocean. That way the ESMs can model the processes of rock weathering and ocean chemistry endogenously.

Comparing the CDR carbon fluxes from IAMs and ESMs allows for an evaluation of the assumed carbon uptake efficiencies in IAMs to improve their representation of the distinct CDR technologies. Running ESMs with endogenous CDR representation makes it possible to address questions on how the climate and the Earth System respond to GMT stabilization with or without overshoot, since the earth system reaction to a ton of carbon removed from the atmosphere may be different from its reaction to a ton of carbon emitted (i.e. addressing the reversibility question). Apart from that environmental impacts, side effects and potential co-benefits of CDR can be assessed in higher detail when spatially explicit climate data is combined with the spatially explicit representation of CDR pattern (e.g. of bioenergy crop production, quicklime distributed to the ocean, rock spread to the field or areas being converted into forests).

4.13 Knowledge Gaps and ScenarioMIP

The ScenarioMIP scenarios span the plausible range of future transformation pathways with a particular focus on emissions and land-use developments. This information is useful and forms the basis for addressing a broad range of research questions, especially for the interaction with ESMs and IAV. The research in socioeconomic systems and policy to fill knowledge gaps is limited and will be more adequately addressed in detail in subsequent research. We provide a short overview what the relationship of ScenarioMIP to the research questions is.

The ScenarioMIP scenarios can serve as a guide for the choice to benchmark policies such as the NDCs and the GST (Section 4.1).

The emission scenarios are associated with carbon prices pathways and therefore the level and shape of the different scenarios provide a useful guide for the level of policy ambition that is necessary to achieve these different emission levels (Section 4.2).

The role of differentiated interest rates and risk premia is not a priority in ScenarioMIP and will be addressed in more dedicated research (Section 4.3). This will be of great interest to identify mechanisms for international climate finance.

The cost reductions of low-carbon technologies are part of the model and scenario assumptions in ScenarioMIP. Additional research is useful to regularly update the assumptions and explore possibilities to further reduce the costs (Section 4.4).

The ScenarioMIP framework is designed deliberately to not include additional future climate impacts and feedbacks on the transformation pathways (Section 4.5). This is going to be a major focus in future research as the IAMs will become more integrated with ESMs and IAVs to fully close the loop.

The recent succession of serious crisis is considered in the ScenarioMIP scenarios by putting more focus on the SSP3-type narrative that forms the basis for the High scenario (Section 4.6). More research will be useful to investigate the risks of climate change and the special challenges in such a geopolitical environment for international climate policy.

In ScenarioMIP the assumptions of economic development are widely varied to capture vastly different futures (Section 6.2). The discussion about post-growth scenarios will require an improved foundation in the overall macroeconomic and socioeconomic context and an improved interaction with researchers from developing and emerging economies (Section 4.7).

The evaluation of SDGs in the context of the ScenarioMIP scenarios will be a politically very important and a scientifically very promising field of research (Section 4.8).

The discussion of intragenerational fairness is not a major focus within ScenarioMIP (as is widely accepted), but a major policy and research priority in the coming years (Section 4.9).

The analysis of residual fossil fuel use in low-emission scenarios (Section 4.10) is a major research priority and can be discussed with the ScenarioMIP scenarios (see Section 6.5.2.1).

The integration of land-use policies into the broader climate mitigation policy framework is of increasing urgency as Land-Use emissions are very sensitive (Section 4.11).

For an improved interaction with Earth System Models the interface between IAMs and ESMs needs to be improved (Section 4.12).

It should be added that over the course of the project horizon the quantification of Direct Human Forcers has emerged as an additional major research need.

5 The REMIND-MAgPIE Modelling Framework

The REMIND and the MAgPIE models are both equilibrium models that apply optimization methods to derive market equilibria. Also, both models cover the time horizon up until 2100 and are global in scope differentiating the world into macro-regions that form markets for food and energy for which market equilibria are computed. Both models rely on the SSPs for assumptions on socioeconomic drivers for demographic, economic, and technological development (Dellink et al. 2017; KC and Lutz 2017).

In this study, both models use different assumptions for the socioeconomic drivers. Generally, SSP2 is used. For the VLLO scenario SSP1 and for the High scenario SSP3 is used. Assumptions on technological development, resource potentials, etc. in REMIND and MAgPIE follow the SSP narratives that are documented in the literature (Kriegler et al. 2017; Riahi et al. 2017).

5.1 The Energy-Economy Model REMIND

REMIND is a Ramsey-type general equilibrium model of economic growth with a hard-coupled detailed energy system model that applies optimization methods to find a general market equilibrium (Bauer et al. 2018a; Bauer et al. 2012; Luderer et al. 2013). Economic agents are assumed to have perfect foresight on future prices, which implies a rational expectations equilibrium on all markets. The macroeconomic system demands labour, capital and final energy. Final energy use gradually modernizes with growing shares of electricity and gases, whereas shares of liquids and solids decrease.

The energy system is a detailed representation of all relevant energy flows from primary to final energy as well as associated GHG emissions. The energy system transformation is consistent with basic energy economic principles of cost competition, but also represents inertia of infrastructures and rigidities to ramp-up new capacities as well as endogenous technological learning.

Regions are endowed with fossil fuels, uranium, and biomass that are traded internationally subject to transportation costs and infrastructure expansion rigidities as well as balance of payments constraints. Coal, gas and biomass conversion capacities that produce electricity, liquids, and hydrogen can be equipped with CCS. An injectivity constraint limits the annual injection of CO_2 into geological formations to 0.5% of the total potential in each region.

5.2 The Land-Use Model MAgPIE

MAgPIE is a partial equilibrium model of the land-use sector that finds market equilibrium by minimizing the global costs of production given price-irresponsive demands for agricultural products (Humpenöder et al. 2018; Popp et al.2014). The model assumes adaptative expectations for evaluation of long-term investment decisions implemented by a recursive dynamic model structure.

The model is driven by demands for agricultural commodities, which are calculated based on population and income projections for the twenty-first century. For meeting the demand, the model endogenously decides, based on cost-effectiveness, about the level of intensification (yield-increasing technological change), extensification (land-use change), and production relocation (intraregionally and interregionally through international trade). CO_2 emissions from land-use change are calculated based on differences in carbon stocks for different land types. The calculation of N_2O and CH_4 emissions from agricultural production is based on IPCC 2006 emission guideline factors. The optimization process is subject to various spatially explicit

biophysical conditions such as yields, water availability, and carbon stocks, which are derived by the global crop growth, vegetation, and hydrology model LPJmL (Schaphoff et al. 2018).

Due to computational constraints, spatially explicit input (0.5-degree resolution) is aggregated to typically 200 simulation units for the optimization process based on a k-means clustering algorithm.

MAgPIE simulates two types of biomass feedstock production: 1st- and 2nd-generation biomass feedstocks. First-generation biomass relies on conventional food crops such as maize and sugarcane. Supplies and demands of 1st-generation feedstocks are prescribed by exogenous policies. The largest potential is offered by dedicated 2nd generation herbaceous and woody lignocellulosic bioenergy crops (such as miscanthus, poplar, and eucalyptus), which feature significantly higher energy-specific yields per hectare than 1st-generation crops. Lignocellulosic feedstocks can be converted into electricity, hydrogen, synthetic gases, and liquid fuels also in combination with CCS. Conversion into heat and solid energy carriers are available, but cannot be combined with CCS. Residues are scaled with production volumes in forestry and agriculture reaching a long-term maximum global potential of 70 EJ/year.

5.3 The Coupling

The integrated assessment of climate change mitigation policies regarding the interdependencies between the energy and the land-use sector requires the explicit representation and consistent solution of both, quantities of bioenergy and GHG emissions and their associated prices. These variables are key features in transformation pathways of energy and land-use systems. Since the REMIND and the MAgPIE model are each numerically heavy a full integration of both models using a hard-link is not achievable. Therefore, a soft-link approach is implemented to derive consistent scenarios with REMIND and MAgPIE (Bauer et al. 2008; Messner and Schrattenholzer 2000). Basically, the soft-link approach feeds REMIND results iteratively through MAgPIE to deliver information for updating assumptions in REMIND; moreover, both models use harmonized assumptions on narratives and quantitative drivers consistent with SSPs. The iteration is repeated until changes between iterations become negligible. The resulting scenarios of REMIND and MAgPIE are consistent regarding price and quantity of bioenergy and GHG emissions. Variations in climate policies or drivers shift these prices and quantities and the underlying energy and land-use scenarios.

For a convergent solution of the soft-link approach, the interdependencies need to fulfil certain conditions:

1. Higher emissions prices decrease GHG emissions from the energy and the land-use sectors;
2. Higher emissions prices decrease fossil fuel use and increase bioenergy demand (this is not necessarily the case for all IAMs under all circumstances; see Bauer et al. 2018a, b);
3. Higher emissions prices increase biomass supply costs;
4. Higher bioenergy prices decrease bioenergy demand; and
5. Higher biomass supply increases marginal costs of biomass supply and land-use GHG emissions.

The interdependencies suggest a unique solution that can be approximated using an iterative soft-link approach. The technical implementation of the iteration process involves (i) a reduced form model that emulates MAgPIE within REMIND and (ii) additional constraints to the solution space to improve the convergence speed and stability of the iterative approach towards the solution.

The REMIND model derives in each iteration scenarios for bioenergy use and emission prices for all regions and time periods. The reduced form model consists of the supply function mapping bioenergy prices to quantities and land-use sector emissions of CO_2, CH_4, and N_2O as exogenous constraints. Given this information in each iteration, REMIND derives a set of emission prices and bioenergy use.

The output of each REMIND run is fed into the MAgPIE model denoted as the mapping to derive updated information on bioenergy prices and GHG emissions.

In the initial iteration, REMIND starts with an initial set of supply curves for bioenergy that are derived from a large set of MAgPIE runs, in which the time paths for biomass feedstock production are varied. The function's parameters are updated in each iteration to correct for differences between initial and actual MAgPIE runs. The main reason for updating the supply function is that its shape in each period depends on the time path of biomass deployment and the carbon emission price that is endogenously derived in REMIND. For enhanced consistency between REMIND and MAgPIE scenarios, approximation errors of the supply curve are reduced and made consistent with the MAgPIE model. Carbon price changes affect biomass feedstock production costs and, therefore, it is necessary to adjust the supply curves to derive consistent sets of price and quantity in the coupled REMIND-MAgPIE model.

The iterative information exchange between both models defines a sequence that converges towards a fixed point for prices and quantities of emissions and bioenergy that is unique for all time steps and regions because of qualitative dependencies 1.-5. mentioned above. The iterative approach is robust and converges for a broad range of socioeconomic assumptions and emission reduction policies.

5.4 Implementation of ScenarioMIP into the REMIND-MAgPIE Model

The implementation of the requirements formulated in the ScenarioMIP process and reported in the framework paper relate to the reference scenarios including the updates and the implementation of the policies that have been assumed.

5.4.1 Model Improvements and Reference Scenarios of updated SSPs

Five major changes have been introduced to the reference scenarios compared with the original SSPs.

First, the socioeconomic drivers have been updated to the latest information. The new scenarios for demographic and economic development are introduced below. The demand trajectories for energy, food, and materials have been also updated as well. Moreover, the emissions have been updated to improve the matching of scenario results with historic data, which is, in particular, the latest version of the Community Emission Data System (CEDS, Hoesly et al., 2018) and Land Use Historic (LUH, G. C. Hurtt et al., 2020). Residual differences will be closed by harmonization procedures that have been documented (Gidden et al., 2019) and that are explicitly mentioned in the ScenarioMIP set-up and time schedule (van Vuuren et al., 2025, in review). These data sets are also used by the Earth System Models (ESMs) for the historic spin-up. These are updates to the datasets used in CMIP6. Therefore, the scenarios will be up-to-date and consistent with historic data and fully compatible with ESMs participating in CMIP7.

Second, the techno-economic assumptions of energy technologies are regularly reviewed and updated, particularly the lower floor costs of technologies such as Solar PV have been revised downwards (Creutzig et al. 2017, Luderer et al. 2022). The resulting values are provided below in Section 6.5.2.2.

Third, the energy sector modelling has been improved by increasing the detail of electricity sector modelling with a particular emphasis on representing integration of fluctuating renewables into the electricity sector (Ueckerdt et al 2015) as well as the use of electricity to produce synthetic hydrocarbons that also relate to technical carbon capture (Odenweller et al. 2025). Another improvement is the more accurate regional differentiation of technology costs (Zhang et al. 2020).

Fourth, the REMIND-MAgPIE model has been further developed and improved. In particular, the details of energy end-use sectors have been substantially improved. For example, the industry sector is now divided into four sub-sectors: cement, iron & steel, chemicals with a special treatment of plastics and an aggregate "Other" sector that covers all other industrial activities, such as construction, manufacturing, food processing, etc. Also, the transport sector has been substantially improved and covers now a broad range of transportation modes for passenger and freight that can be supplied by specific alternative modes (Rottoli et al. 2021). The buildings and services sector have been updated to include a detailed representation of energy demands. This mostly refers to the modelling of heating and cooling, with heating-pumps enabling deeper electrification of the buildings sector (Levesque et al. 2018, 2021). In the land-use sector the explicit modelling of the forestry sector has been added and therefore broadens the analysis by including additional carbon stocks and flows as well as land-use competition (Mishra et al. 2021). These improvements enrich the information basis and also lead to changes in transformation dynamics.

Fifth, the new model version represents a much broader set of Carbon Dioxide Removal (CDR) technologies (Strefler et al. 2021b). The original SSP version only represented Bioenergy with carbon Capture and Storage (BECSS) explicitly. The model version used for ScenarioMIP also represents Afforestation and Reforestation (Humpenöder et al. 2014), Enhanced Weathering of basaltic rocks (Strefler et al. 2018), Ocean Alkalinity Enhancement, Direct Air Capture (Broehm et al. 2015, Kowalczyk et al. 2025) and bioenergy use in the Industry Sector (i.e. cement production) combined with CCS. Note that the carbon capture alternatives are not necessarily connected to geological storage, but can also deliver CO_2 as a feedstock for the production of synthetic hydrocarbons.

On top of the improvements and updates of the energy, industry, land and carbon management sectors the overall scenario logic has been adapted to the new realities. baseline scenarios are now formulated as weak policy scenarios. In the original edition of the SSPs, the baseline scenarios did not consider existing and projected climate policies. This is now different. The baseline scenario includes a set of weak climate policies that replicates the National Policies as they are implemented (NPi) and projects gradual tightening and regional convergence over the 21st century. This implies that in the base-year period the historical emissions are actually lower than in a counterfactual no-policy case. For instance, the High emission scenario in ScenarioMIP assumes a roll-back of these weak policies after 2025 and therefore the emissions revert back to the no-policy case. Thus, the emissions in the roll-back scenario are higher than in the baseline scenario.

5.4.2 Emission and Climate Targets

Table 1 provides an overview of the described assumptions. It also shows the sensitivities regarding the speed of convergence to a globally uniform level that were explored with the REMIND-MAgPIE model to study the effects on regional emissions and global climate outcomes.

As the High scenario explores the high end of temperature outcomes under climate policy rollback and the Medium scenario extends current policies, there are no global climate or emission targets in these scenarios.

In all other scenarios, the main policy instrument to implement global emission and climate targets are carbon prices. In this subsection, we describe the global targets and refer to the next Section 5.4.3 for the description of regional carbon price differentiation.

In the Medium-Low scenario, carbon prices reflect current policies until 2040. Thereafter, the global reference carbon price increases linearly until 2100 and is adjusted so that net-zero CO_2 emissions are reached globally in 2100. Convergence to a globally uniform carbon price is slow in this scenario.

In the Low scenario, carbon prices in 2030 reflect NDCs that can still be plausibly achieved. The global reference carbon price then increases linearly until the time of global net-zero CO_2 emissions and is adjusted to ensure that peak warming remains below 2°C (67%) based on the simple climate model MAGICC7. After reaching net-zero CO_2 emissions, the global reference carbon price features a moderate linear increase so that global net-zero GHG emissions are reached in 2100. Regional carbon prices converge with an intermediate speed to a globally uniform level.

Table 1: Overview of Climate Policy Assumptions

Scenario	Near-term assumptions	Long-term assumptions	Convergence to globally uniform carbon price
High Emissions (H)	Rollback of current policies	No climate policy	Not applicable
Medium Emissions (M)	Current policies	Extension of current policies	Not applicable
Medium-Low Emissions (ML)	Current policies until 2040	Net-zero CO2 in 2100	Slow
Low Emissions (L)	(Plausible) NDCs in 2030	Well below 2°C	Intermediate (Sensitivities: Fast, Immediate)
Very Low with Limited Overshoot (VLLO)	"As low as plausible"	Lowest plausible peak warming	Fast (Sensitivity: Immediate)
Very Low after High Overshoot (VLHO)	Current policies in 2030	Lowest plausible 2100 warming (after high overshoot)	Intermediate (Sensitivities: Fast, Immediate)

Source: own compilation.

In the Very Low with Limited Overshoot scenario, carbon prices in 2030 are chosen to achieve regional emission reductions which are considered "as low as plausible". Thereafter, the global reference carbon price features a strong linear increase to 500$ per ton of CO_2 (USD2017) in 2050, which was judged to be at the upper end of the plausible range in view of the resulting energy and land system transformation in REMIND-MAgPIE. After 2050, the global reference carbon price features a moderate linear increase. Convergence to a globally uniform carbon price is fast in this scenario.

In the Very Low after High Overshoot scenario, carbon prices in 2030 reflect current policies. The global reference carbon price thereafter increases exponentially with a rate of 4.5%

(corresponding to the average interest rate of the model) until 2100. Compared to the linear increasing carbon prices in the other scenarios, this implies relatively lower carbon prices in the near-term but very high carbon prices towards the end of the century. It thereby models delayed increase in climate policy ambition and a strong commitment to carbon dioxide removal in the second half of the century. Regional carbon prices converge with an intermediate speed to a globally uniform level.

5.4.3 Regional Carbon Price Differentiation

In each scenario, regional carbon prices in 2030 reflect the near-term assumptions on climate policy (see Table 1). Moreover, the scenario-specific global reference carbon price reflects the long-term assumptions. From the modeling perspective, it remains to specify the convergence from the regional carbon prices in 2030 (or 2040 for the ML scenario) to the global reference carbon price.

We consider four different speeds of convergence (see Table 2): First, immediate convergence means that all regions immediately adopt the global reference carbon price in 2035. Second, fast convergence means that OECD regions implement the global reference carbon price from 2040 and non-OECD regions converge to the global reference carbon price until 2050. Third, intermediate convergence also means convergence by 2040 for OECD regions, but for China, Middle East, North Africa, Latin America and Reforming Countries, convergence is delayed to 2060, and Sub-Saharan Africa, India and other Asian countries reach the global reference carbon price in 2070. Finally, slow convergence of carbon prices assumes that OECD regions adopt the global reference carbon price from 2050, China, Middle East, North Africa, Latin America and Reforming Countries from 2080, and Sub-Saharan Africa, India and other Asian countries from 2100.

Moreover, the type of convergence to the global reference carbon price is differentiated by region. While OECD regions converge quickly (interpolation exponent equal to 1 means linear convergence), other regions converge slower (interpolation exponents larger than 1 represent a convex shape,[16] for example, quadratic convergence if the interpolation exponent is equal to 2).

[16] Convex shape means that the convergence is relatively slow in early years, but speeds up in latter period up until the year of convergence.

Table 2: Region-specific assumptions on convergence year and type of convergence to the global reference carbon price

Regions	Convergence year Immediate (2035)	Convergence year Fast (2050)	Convergence year Intermediate (2070)	Convergence year Slow (2100)	Interpolation exponent
Australia, Canada, Europe (EU and non-EU), Japan, New Zealand, United States	2035	2040	2040	2050	1
China, Middle East, North Africa, Latin America, Reforming Countries	2035	2050	2060	2080	1.25
Other Asia	2035	2050	2070	2100	1.5
India	2035	2050	2070	2100	2
Sub-Saharan Africa	2035	2050	2070	2100	3

Source: own compilation.

5.5 Climate Evaluation with MAGICC tuned to CMIP6

For evaluating the climate outcomes of the scenarios, we apply the same method used in the AR6 WGIII. The AR6 climate assessment of mitigation scenarios (Kikstra et al. 2022) consists of three main steps. First, the global emission trajectories of all relevant GHGs are harmonized to historical data, ensuring that emissions from all scenarios start from the same values in 2015. Then, emissions of relatively less important species that are not reported by the model, such as those of certain minor CFCs, are infilled using other scenarios from other models in the AR6 database as a reference. Finally, the Simple Climate Model (SCM) MAGICC v7.5.3 (Meinshausen et al., 2022) is run using the harmonized and infilled emissions. For each scenario, 600 realizations of MAGICC are run, using an ensemble of parameter sets calibrated to closely reproduce historically observed warming, warming projections for standard scenarios, and the uncertainty range in key physical climate parameters assessed by the IPCC Working Group I (Foster et al. 2021). Here, we show mainly results for global surface air temperature (GSAT) change relative to the pre-industrial period (1850-1900), which is normalized to reflect the observed warming of 0.85K in the 1995-2014 period in all realizations, and refer to warming percentiles of the 600 realizations.

It's important to keep in mind that, as part of the ScenarioMIP process, some updates to this climate assessment methodology are expected in the near future. Although warming results are not expected to change substantially, updates in the method and references used for the harmonization of emissions might lead to appreciable differences in the emission magnitudes of some gases, especially in the near-term.

6 Results

6.1 The database

We use runs applying the ScenarioMIP protocol with the REMIND-MAgPIE model and compare these results with the SSPs and the Illustrative Mitigation Pathways IMPs from the WG3 report of the AR6. For historical data we use different sources. In particular we use CEDS and EDGAR (Hoesly et al. 2018, Minx et al. 2021). The Community Emission Data System CEDS is the common source for model harmonization that the Earth System Models use and to which the IAM emission results are harmonized before they are input to the ESMs. EDGAR is a data source that is also used by WG3 of the IPCC for the analysis of historic emission trends (Minx et al., 2021).

At present (August 2025) the runs of ScenarioMIP are not finalized and the Marker models for the different scenarios have not been selected. Thus, we only use the REMIND-MAgPIE model for the new ScenarioMIP scenarios relying on not yet finalized results.

6.2 Demographic and Socioeconomic Drivers

The projections of demographic dynamics are done by the Wittgenstein Center while the projections for economic growth and development for the SSPs are done by the Environmental division of the OECD. This is the only contribution these institutions provided within the SSP and the ScenarioMIP process. This institutional setting separates the development of demographic and socioeconomic scenarios from the assessment of transformation pathways and climate policies. This separation also assumes that the fundamental factors that influence the socioeconomic drivers within the SSPs are not affected by the policy choices within each SSP. Also, the IAV modelling teams use the same socioeconomic data for their models and analysis.

The projections for population and economic development have been updated in early 2024; smaller revisions were added later. The modelling tools for the updates are incremental improvements of those developed and applied for the original SSPs. The SSP narratives, i.e. the qualitative depictions of the SSPs (Riahi et al. 2017), have been maintained, only the quantifications have been updated.[17] Most importantly for recent events the new projections have taken care of the recent shock and recovery induced by the COVID-19-pandemic 2020-2022. The updated version also has reflected the most recent developments in demographic and economic developments. The new versions will be introduced below. Here we present material at an intermediate stage. Full documentation and publication of the updated scenarios including comparisons with previous versions and alternative scenarios will become available at a later stage by the original institutions.

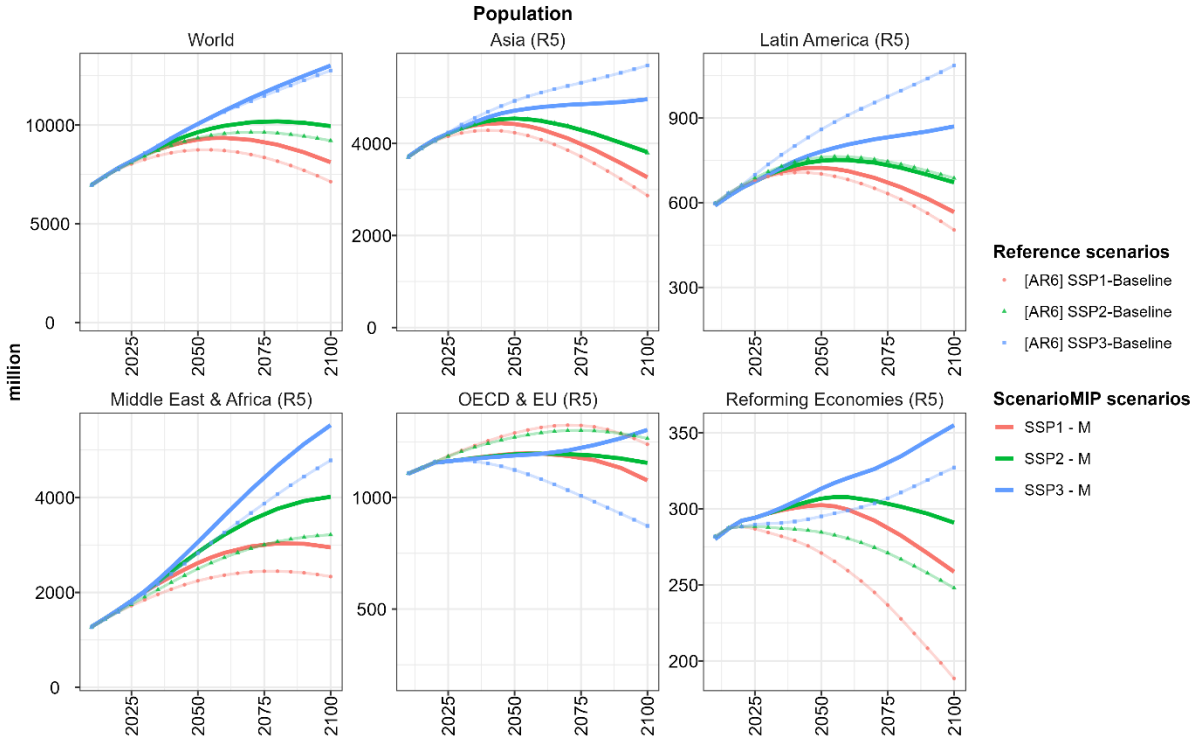
6.2.1 Population Dynamics

The population projections have been updated by (KC et al., 2024, see Figure 22 The updated SSPs turn out to project higher population figures. With SSP2 increased from 9.0 to 9.9 billion people in 2100. A major driver are the upward revisions in developing and emerging economies, whereas projections for high income countries in Europe, the Americas and East Asia have been reduced. Most notable, the SSP2 projection for the African continent has been increased from 2.6 billion to 3.5 billion in 2100. The main reasons are changes in child mortality, the slower demographic transition and lower mobility in migration in the countries of the Sub-Sahara region. For instance, this leads to a projected increase of the population of Nigeria in 2100 from

[17] A recording of the launch event webinar can be found here: https://www.youtube.com/watch?v=AzyQhnh3Ajs

580 to 700 million. Thus, the major changes in the global population projection are due to changes in the projections for Africa, whereas the smaller increases in other developing and emerging economies are offset by decreases in developed countries (more details in KC et al. 2024).

Figure 22: Population projections for the updated SSPs compared with previous version



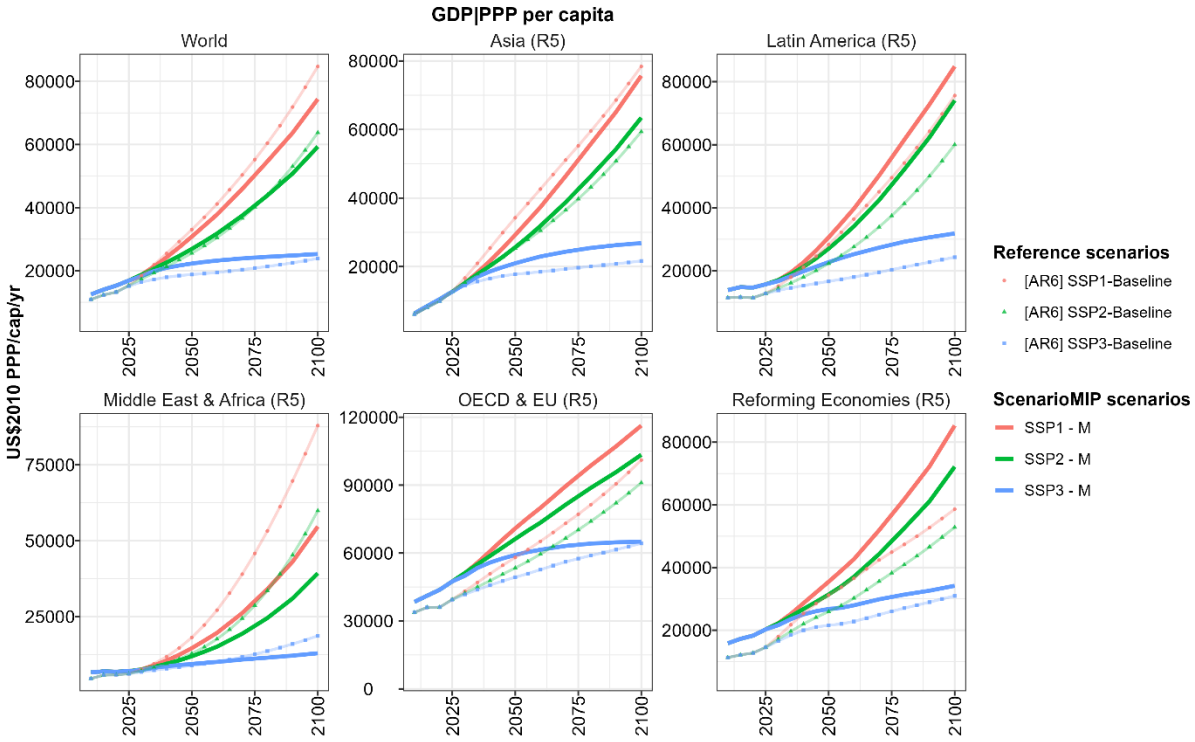
Source: KC et al. (2024) and AR6+ database

6.2.2 Economic Growth and Income Convergence

The original SSP projections of economic development used as input assumptions for the IAMs have been discussed critically in recent years. The projections are exogenous inputs as these projections are developed by the OECD and used by various IAM teams. The equity implications of slow and limited convergence have come under scrutiny. In a nutshell the main line of argument suggests that deep and enduring inequalities in per-capita incomes that are inputs to the IAMs imply unequal outcomes in the entitlements derived as outputs with the IAMs. Consequently, the argument suggests IAMs and the information derived for policy making perpetuates inequalities and might even deepen them, especially if the climate policy ambition is strong. The argument suggests that exogenous growth assumptions for different countries and the associated demands for energy, materials, food, and timber already justify claims and determine burden sharing schemes.

Although we do not agree with the argument because the burden sharing is not determined by the growth assumptions, it is useful to highlight this point up-front because the updated scenarios for economic (Figure 23) will likely reinforce this debate in the context of ScenarioMIP and other new scenarios in preparation of AR7.

Figure 23: Economic growth projections for the updated SSPs and the previous version

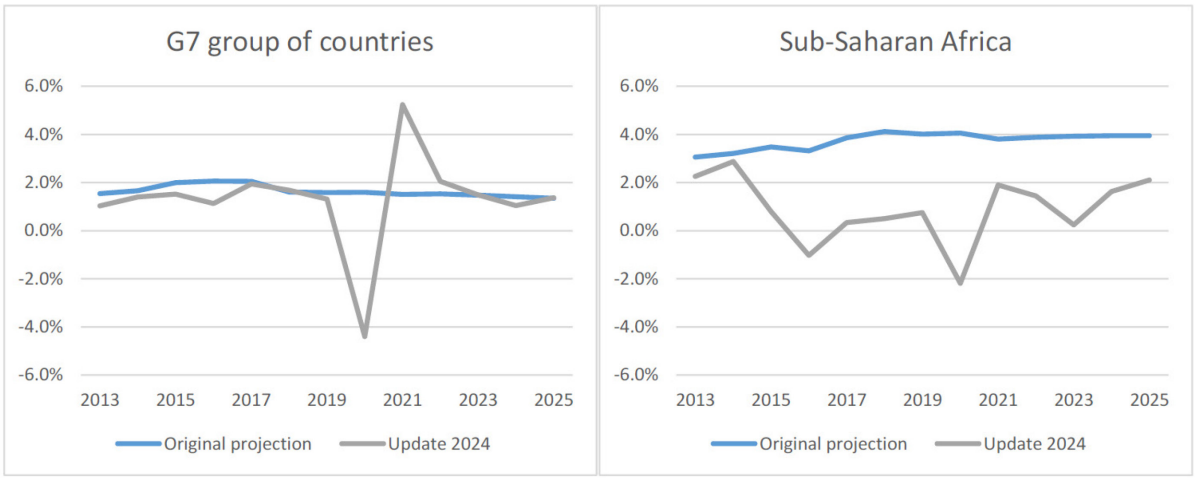


Source Rob Dellink and AR6+.

The update of economic growth projections is based on the same modelling framework as the original tool used for the first edition derivation of the SSPs (Dellink et al., 2017). Part of the update is that the economic projections rely on the new population projections as the input.

At the global level the new GDP projections show lower growth rates in SSP2. This is partly related to the revised population projections. The relatively small downward revisions of population affected the high-income countries, while upwards revisions happened in low and low-medium-income countries. Major additional changes include the update to historic data including the slowdown related to the COVID-19 pandemic, the use of new Purchasing Power Parity conversion factors as well updates to economic growth projections. Figure 24 shows that the original projection for Sub-Sahara Africa was too optimistic as compared to the development that unfolded after the publication in 2017. Note that this is not limited to the COVID-19-pandemic, but the negative deviation already materialized before 2020. Consequently, the near-term projections have been revised downwards. Therefore, these revisions will very likely reinvigorate the debate about inequality mentioned above.

Figure 24: Comparison of growth projections with historical record



Source: The figures are taken from the presentation by Rob Dellink at the launch event on Feb 8, 2024 sent privately by email to Dr. Nico Bauer.

6.3 GHG Emissions

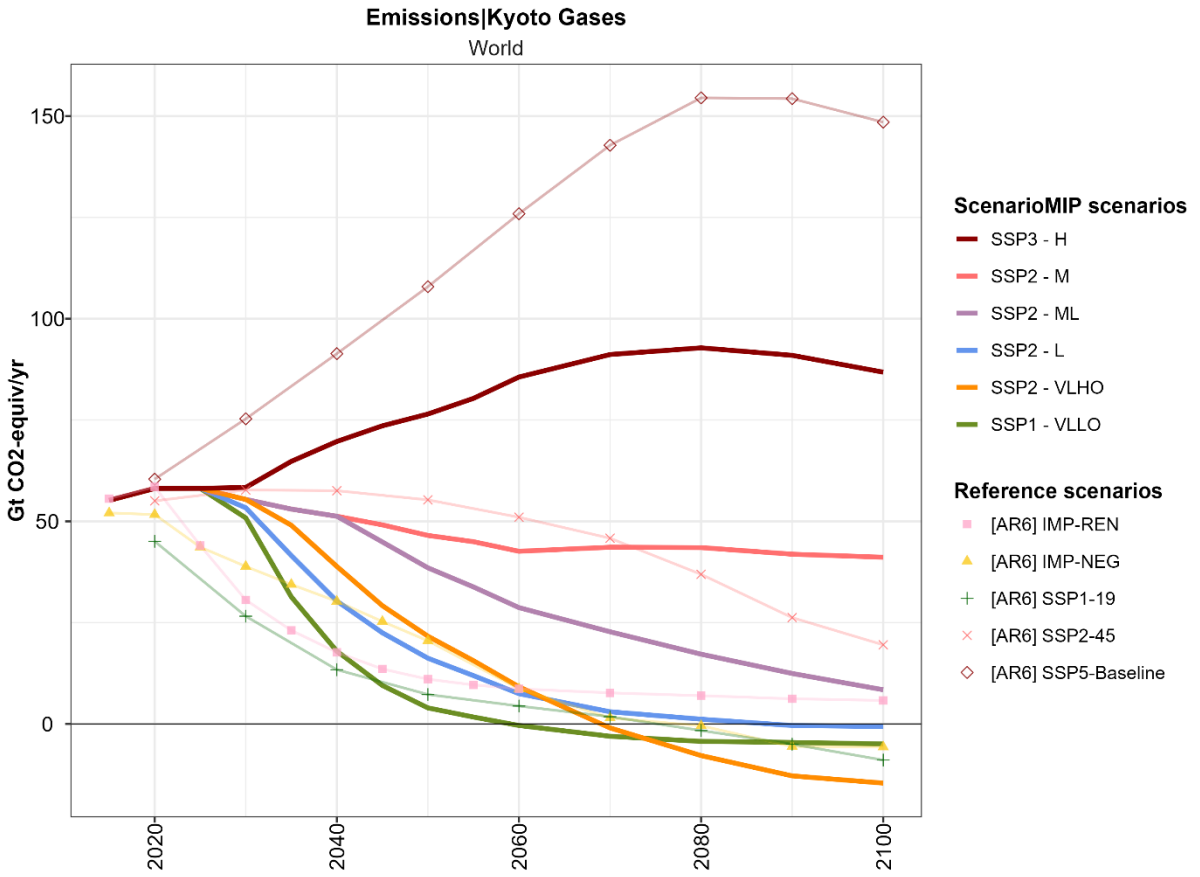
The emissions of the major GHGs – also known as Kyoto Gases – derived with REMIND-MAgPIE are shown in Figure 25 along with the comparison with a subset of the SSPs and the Illustrative Mitigation Pathways of AR6 (Figure 26 below shows the CO_2 emissions from fossil fuel and industry).

In the near-term GHG emissions developed along the SSP2-45 scenario. Thus, the strong increase until 2030 formerly prescribed in the SSP5 baseline has not been realized, but also the very strong decreases in the ambitious mitigation scenarios have not been realized. For the year 2030 this leads to substantially higher emission levels in the new ScenarioMIP ensemble as compared with the older AR6/SSP scenarios.

In the medium- and longer-term the new Medium scenario is lower, but still similar to the original SSP2-45 scenario. It should be noted here that both scenarios are not directly comparable. The new medium scenario assumes climate policies that aim at replicating national policies as implemented (NPi) and assumes an extension of these until 2100 differentiated by regions, whereas the original SSP2-45 explicitly aimed for the 4.5W/m^2 target in 2100, which is the reason for the accelerating emission decline post-2050.

Figure 25: Total global emissions of GHGs

GHGs comprise the six Kyoto gases that are weighted with the 100-year Global Warming Potentials to derive the CO_2-equivalent emissions.



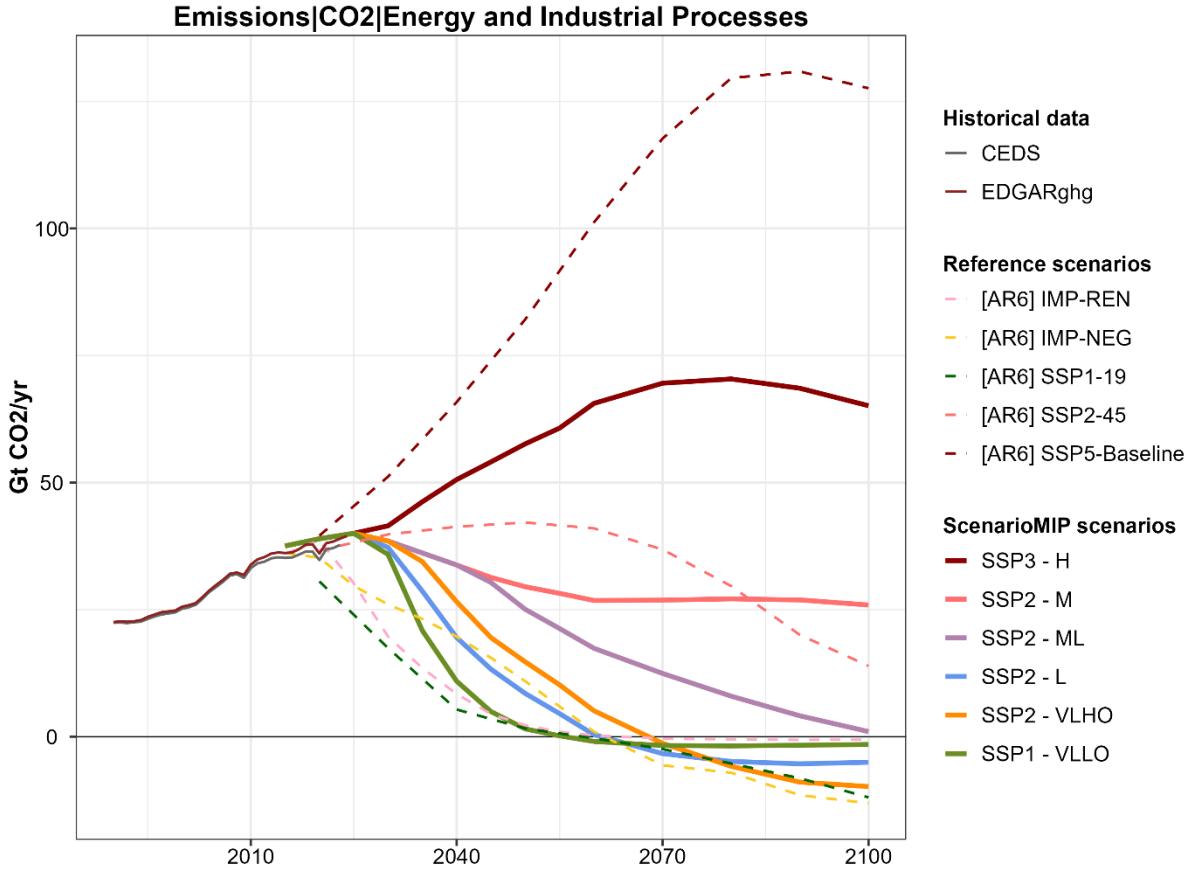
Source: own calculation.

The new High scenario is substantially below the original SSP5 baseline. A main difference is that the REMIND-MAgPIE team has now implemented the SSP3 narrative to represent the reference system for a High scenario. Despite the higher population assumption in SSP3-type scenarios the additional emissions are limited compared with SSP2 because stagnant GDP development and slow income convergence are the dominating forces to slow demand growth for energy, materials and meat-rich diets. In the original version of the SSPs it became clear that SSP5 with the substantially higher GDP growth would lead to high-end emission scenarios. However, the narrative became less and less convincing over the past ten years, and particularly over the past few years, so that the REMIND-MAgPIE team paid greater attention to the SSP3-type scenarios. The updated SSP3 scenario also shows lower emissions than the original SSP3 versions. A major difference is that low-carbon technologies have already improved their economics so that the reliance on fossil fuels has decreased (see Section 6.5.2).

Despite the delay of emission reductions in the group of low emission scenarios (VLLO, VLHO and L) net-zero GHG emissions are reached before 2100. Net-zero CO_2 emissions are reached by 2070 or earlier (see Figure 26). The VLLO scenario even falls below the AR6 scenarios by 2050 and reaches net-zero GHG by 2060, whereas the VLHO scenarios reaches net-zero only by 2070, but then decreases to the deepest level by 2100. Thus, although near-term emission reductions have not been materialized over the past 10 years, the emission reduction potentials are large and could be quickly realized.

Figure 26: Total global CO_2 emissions from fossil fuels and industry

The emissions include all gross CO_2 emissions from Energy conversion, industrial process and land-use and land-use changes as well as removals by technical measures, but not re- and afforestation.

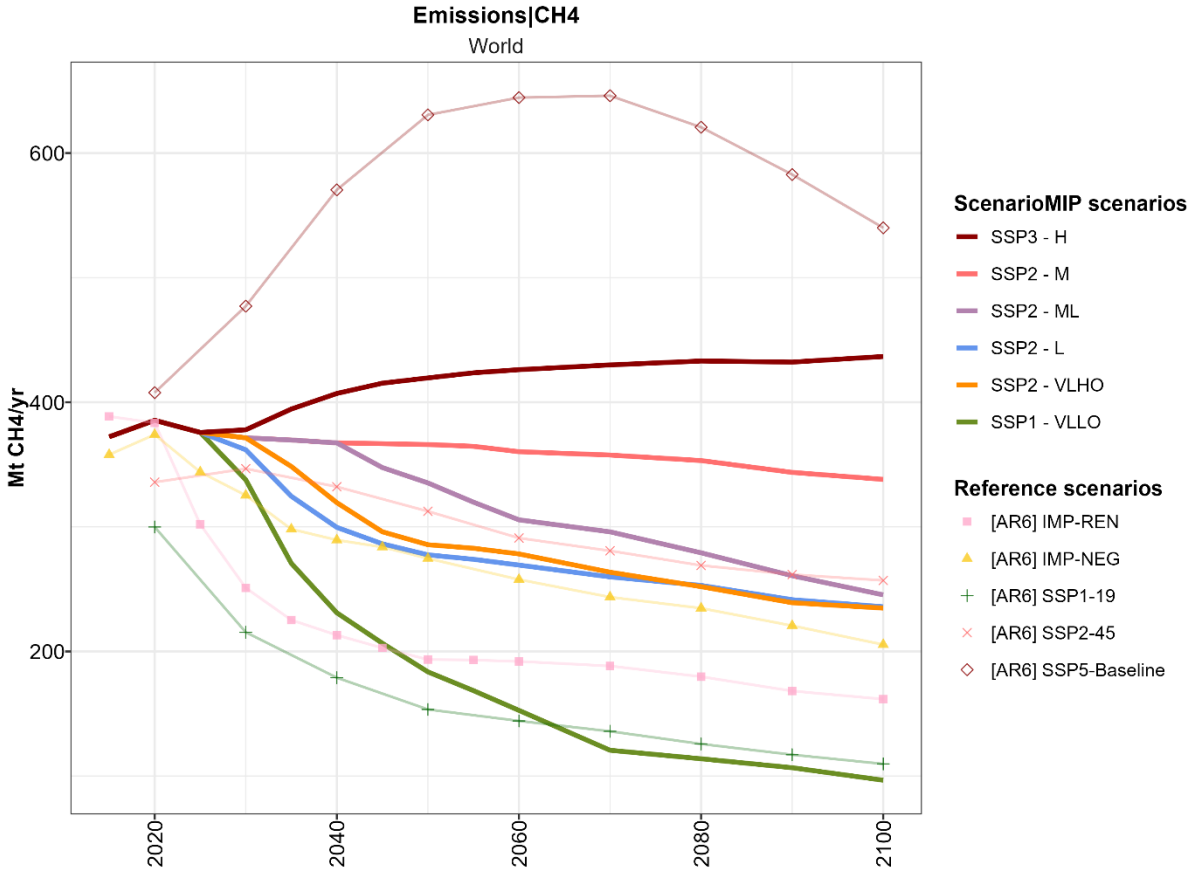


Source: own calculation.

Figure 27 shows the total global CH_4 emissions. In the near-term we also see that emissions are substantially below the projections of the original SSP5 baseline, but also the emission reduction potentials have not been realized in recent years. Compared with the dynamics in the CO_2 emissions (Figure 26) a remarkable difference between the AR6 scenarios and the new ScenarioMIP is that the medium and long-term CH_4 emission reduction potential has not increased, thus the lower bound of the long-term CH_4 emissions is now higher as compared to the SSP/AR6 scenarios. A major reason is that the assessment of technical CH_4 emission reduction potentials has been updated (Harmsen et al., 2019). This can be seen in the limited difference between the Medium and the Low scenario, which is mostly caused by technical mitigation measures. The low CH_4 emissions in the VLLO scenario are driven by the assumptions on dietary changes towards lower meat consumption (Humpenöder et al., 2024).

Figure 27: Total global CH_4 emissions from fossil fuels, industry, waste and land-use

The emissions include all gross CH_4 emissions.



Source: own calculation.

6.4 Carbon removals

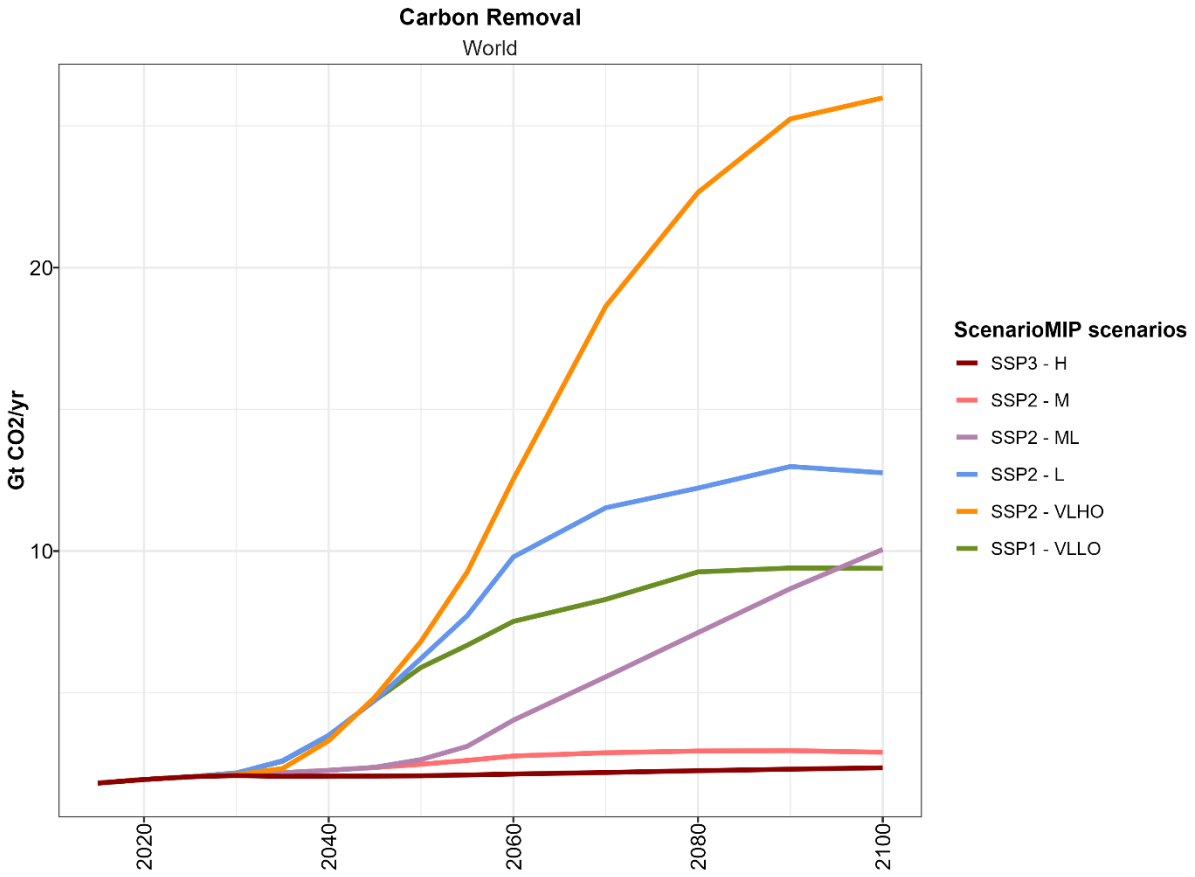
Figure 28 shows the pathway for carbon removals from the atmosphere into various carbon pools (underground geological storage after technical carbon capture, vegetation of managed land, enhanced weathering. As expected, the Medium and High scenario hardly remove any carbon from the atmosphere because of a lack of policy incentives. In the three scenarios of the Low group the near-term ramp-up is nearly identical before 2050, only afterwards marked differences are observed.

The VLLO scenario is constrained in CDR activities as sustainability concerns motivate limitations on geological storage as well as bioenergy production potentials. Land-use related CDR (afforestation and reforestation) is facilitated by the assumptions on changes of dietary choices towards a low-meat diet that reduce the demand for land for food and fodder production by the agricultural sector (see Section 3.5 for more details on scenario specifications).

The very high CDR deployment in the VLHO scenario relies on optimistic assumptions about the performance of DAC, a large-scale deployment of Ocean Alkalinity Enhancement (OAE), the availability of geological storage space and a cooperative institutional setting that facilitates huge CDR activity in specific regions (such Reforming Economies and the Middle East with huge geological storage potentials). Furthermore, strong gains in crop yields are required to facilitate large-scale biomass production that is required for CDR via Bioenergy with Carbon Capture and Storage (BECCS).

The Medium-Low scenario shows a steady ramp-up after 2050 reaching 10 $GtCO_2$/yr by 2100 including storage in long-lived materials. Interestingly, the CDR does not rely on aff-/reforestation but needs to activate technical CDR options including BECCS. The reasons for these differing results are not fully clarified as of now. Important arguments are the path-dependencies in land-use change and yield changes combined with differences in regional climate policies.

Figure 28: Total global CO_2 removals



Source: own calculation.

6.5 Energy Systems Transformation

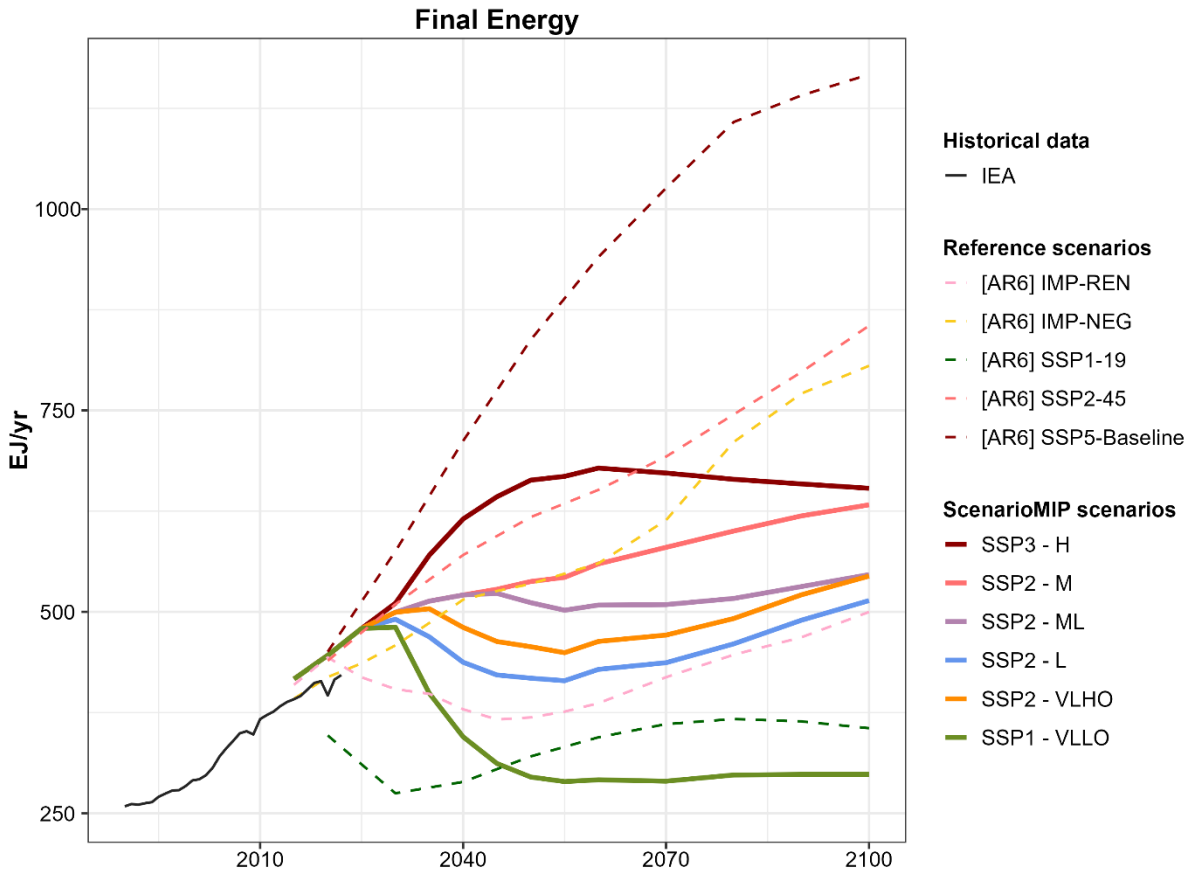
6.5.1 Final Energy Use

Figure 29 shows the global final energy use and the share of electricity in the final energy mix. The VLLO scenario shows a substantial decline in the total final energy use until mid-century that driven by an enormous electrification push. The drop in final energy use does not imply that less energy services are enjoyed and less goods produced over time because electric processes like direct iron reduction, recycling like aluminium and appliances like electric vehicles and heat pumps are much more efficient than non-electric alternatives.

The other scenarios show increasing final energy consumption towards the end of the 21st century, but also lower electrification rates. Particularly the High scenarios features continuously increasing final energy consumption until 2080 and the electrification rate does not exceed 30%.

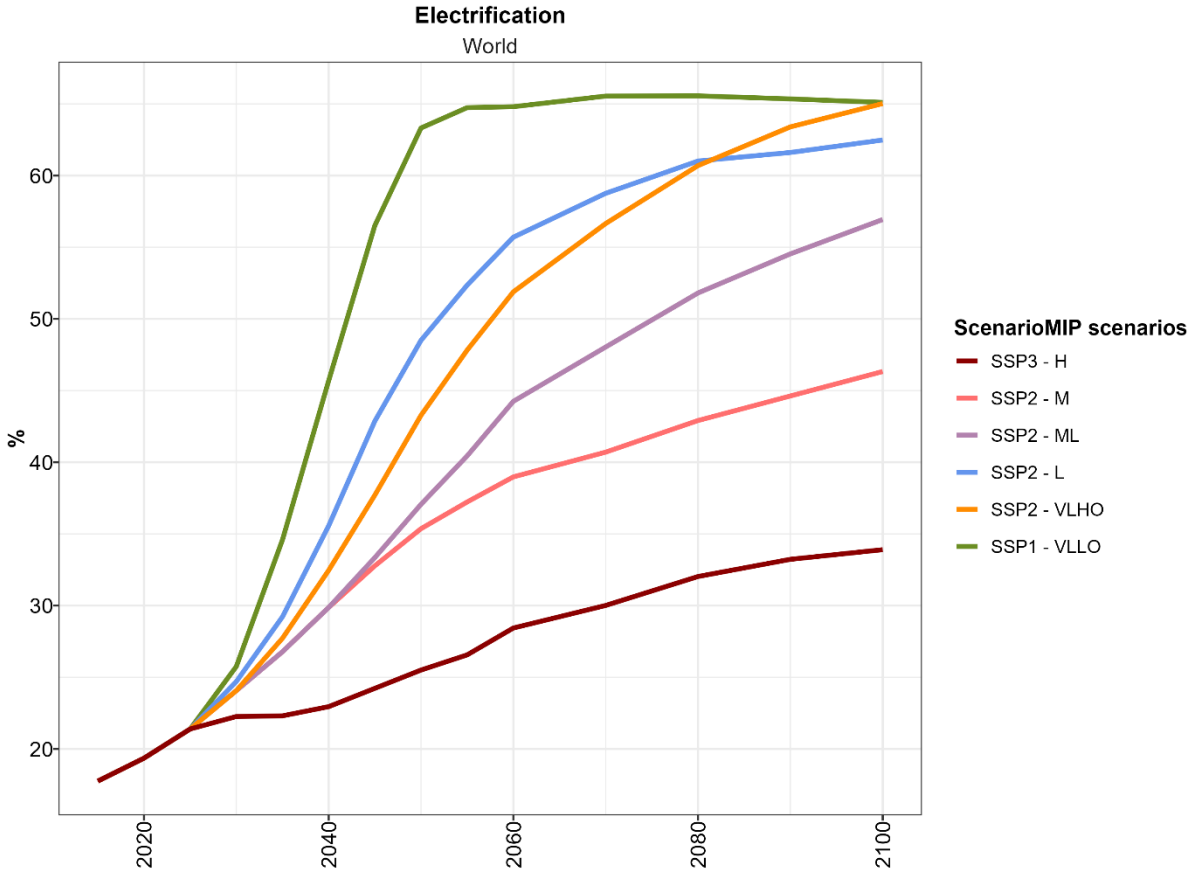
The original SSPs were generally more pessimistic about the modernization of final energy use via electrification and showed generally higher total final energy use, particularly in the coming decades until 2050/60. For instance, by 2050 the original SSP1 scenarios, representing a sustainability-oriented narrative with low demands similar to the VLLO scenario here, showed electrification rates below 35%, while the total final energy use increased to about 450EJ/yr. The original SSP3 scenario featured only stagnant electrification rates, while they increasing in the new edition. Thus, the remarkable technological changes in end-use technologies that have been realized in recent past and that are considered in the new ScenarioMIP scenarios lead to substantially different paths for the total scale and the structure of final energy demand.

Figure 29: Total global final energy use



Source: own calculation.

Figure 30: Global electrification rate



Source: own calculation.

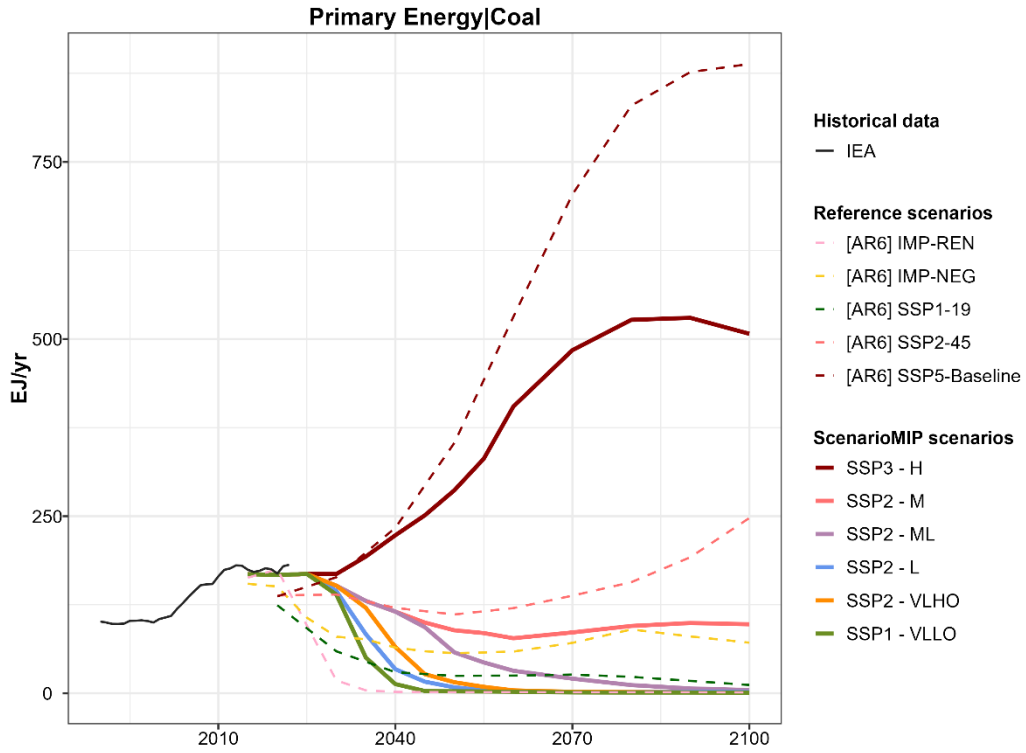
6.5.2 Primary Energy Use

The changes in the structure of final energy use, presented in the previous subsection, interact with primary energy use because electric energy can be produced from renewable energies, whereas non-electric energy mostly consists of combustible energy carriers that are dominated by fossil fuels.

6.5.2.1 Fossil Fuel Use

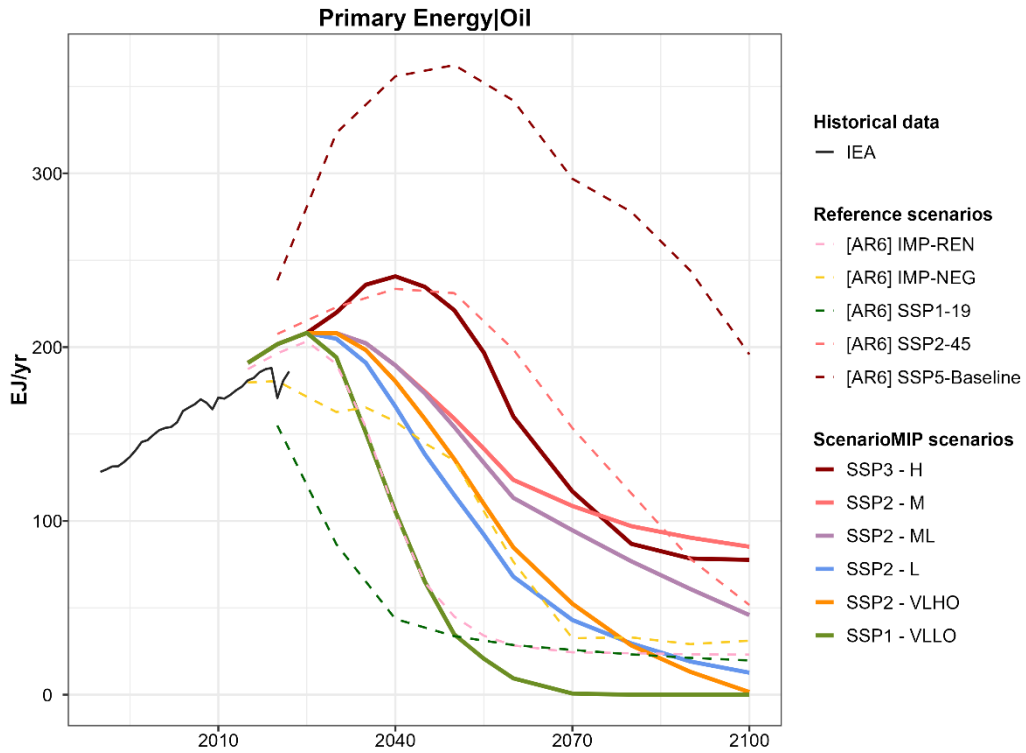
The following figures show the use of fossil fuel fuels for the ScenarioMIP scenarios; Figure 31 for coal, Figure 32 for oil and Figure 33 for gas. In the VLLO scenario fossil fuels are rapidly phased-out. By 2050 only about 50 EJ/yr of residual fossil fuel, mostly oil, remain in the system. Over the following decades fossil fuels are completely phased out in this scenario. The peak of oil use occurs until 2040 (at the latest) in the High scenario. In the High scenario the resurgence of oil use in the coming years is partially triggered by the roll-back of fuel taxes in importing countries. All scenarios project a decline of oil use by 2100 to at most 50% of today's consumption. Note that in the VLHO and the L scenario global oil use declines towards zero by 2100. The very high oil use in the original SSP5 scenario reflected the optimistic assumptions about fossil fuel availability, especially vast amounts of non-conventional oil in developed countries (see Bauer et al. 2016b). These optimistic assumptions are not consistent with the SSP3 narrative that we applied for the High scenario.

Figure 31: Global use of coal



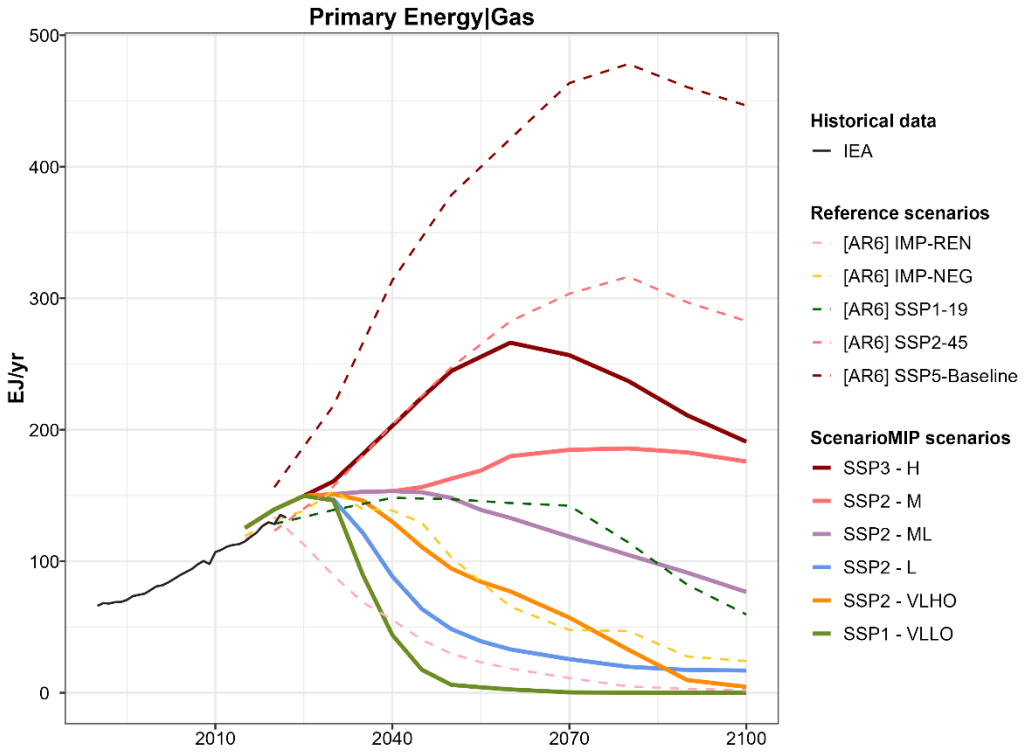
Source: own calculation.

Figure 32: Global use of oil



Source: own calculation.

Figure 33: Global use of natural gas



Source: own calculation.

Gas use shows a wider spread across scenarios than oil. While the phase-out of gas in the VLLO scenario is even faster, the Medium and the High scenario show gas consumption that is higher in 2100 than today. Nonetheless, the levels of the original SSP5 baseline are not reached due to the more stagnant technology assumptions that limit the availability of natural gas in the SSP3 and SSP2 narratives (Bauer et al. 2016b).

The use of coal is generally decreasing, except in the High scenario. The main reason is that the roll-back of climate policies and the high demand for energy, particularly non-electric energy, lead to high coal demand. For instance, in 2100 nearly half of total coal is used to produce liquid fuels, particularly for the transportation and chemical sector. This is similar to the very high coal use in the original SSP5 scenario, but shifted to a lower level because slow economic growth in developing countries mutes total demand growth for transport and liquid fuels compared with the original SSP5 scenario. It should be noted that the REMIND-MAgPIE model does not consider all coal extraction technologies (Bauer et al. 2016b). For instance, the concept to gasify coal in-situ and produce the synthesis gas is actively pursued and in recent years commercial successes have been achieved with this technology.[18] This technology is a serious climate risk. If underground coal gasification (UCG) became available the costs of fossil energy production could be potentially reduced and the fossil reserve base could be increased by a large amount because UCG makes unmineable, deep and abandoned coal seams available.

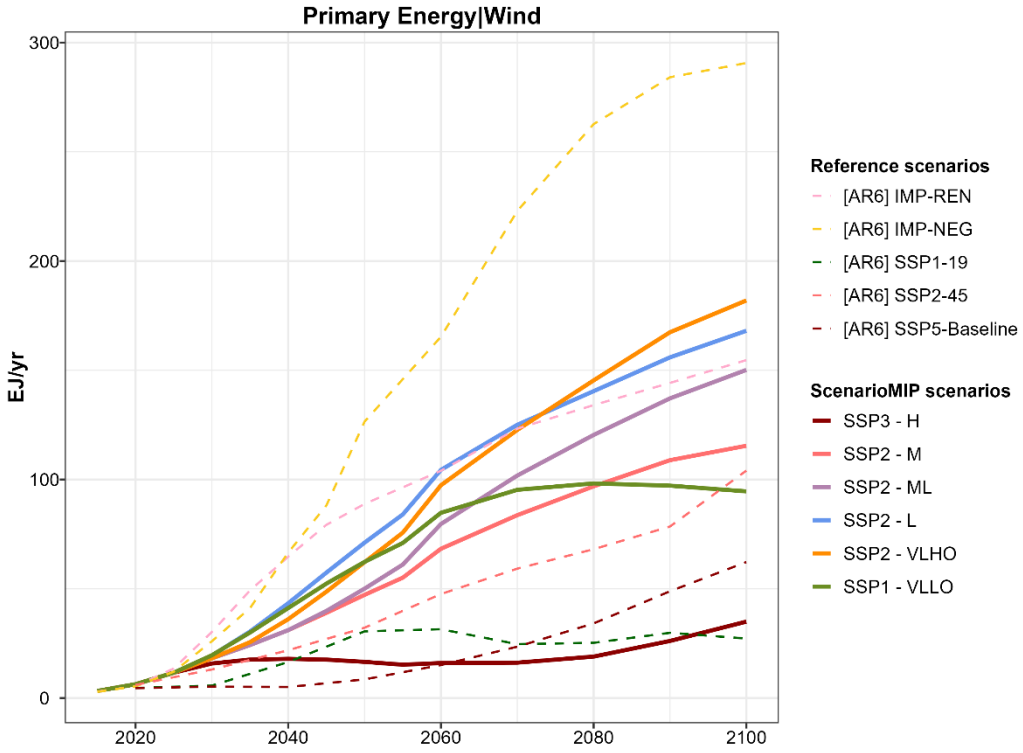
The rapid decrease of coal use in the strong mitigation scenarios is well-understood (Bauer et al. 2016a, 2018a). The end-user price of coal is very sensitive to CO_2 pricing policies and coal can be relatively easily replaced by renewables in the power sector and by alternative energy carriers, such as electricity and hydrogen in end-use sectors.

[18] https://reneweconomy.com.au/south-australia-about-to-set-fire-to-underground-coal-and-its-green-energy-credentials/

6.5.2.2 Renewable Energy

The new generation of scenarios shows robust growth in global wind and solar electricity production as shown in Figure 34 and Figure 35, respectively. The growth is generally stronger in Solar PV than in Wind generation. This leads to substantial decline of shares in other electricity generation technologies. The robust growth in all scenarios, except the High emission scenario, is driven by relatively low and further decreasing investment costs for Wind and Solar PV, combined with relatively high and increasing costs of producing electricity with other technologies, particularly fossil based generation that is also subject to carbon pricing policies.

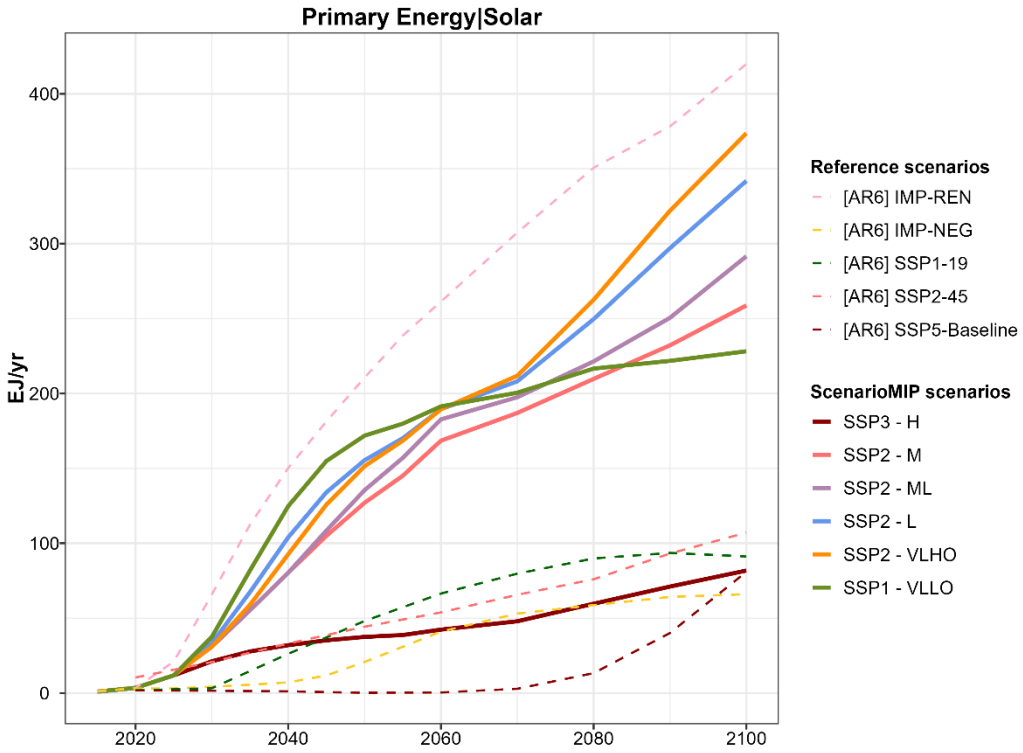
Figure 34: Global production of wind electricity



Source: own calculation.

In the Medium scenario Wind and Solar PV contribute about 350EJ/yr in 2100. The SSP2-45 scenario of the original SSPs achieved less than half of this value. Similarly, the SSP1-19 scenario shows substantially lower renewable deployment than the more stringent mitigation scenarios of ScenarioMIP. Only the more recent IMP-Ren shows higher Solar PV generation. The new VLLO scenarios is comparatively low towards the end of the 21st century because efficiency improvements lower the demand for overall energy, which is part of the scenario narrative.

Figure 35: Global production of solar electricity



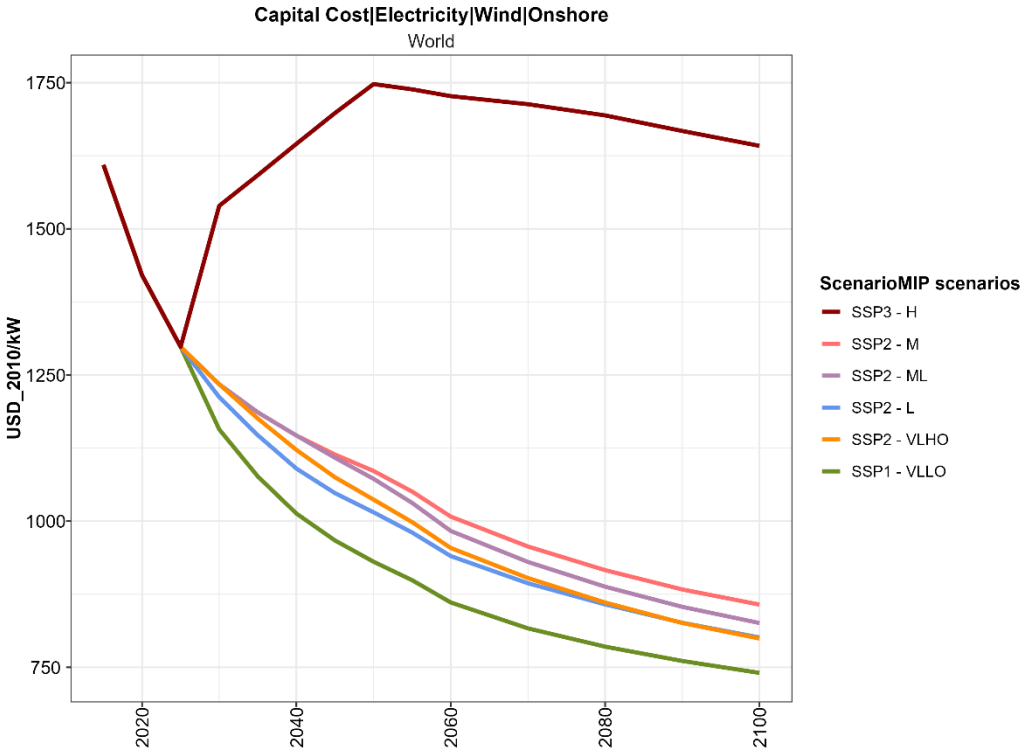
Source: own calculation.

Interestingly, in ScenarioMIP also the High scenario shows robust growth of Solar PV and stagnant levels of wind electricity production. In the original version of the SSPs the deployment of Solar PV only kicks-off towards the end of the 21st century. This reflects the lower investment costs that improve the supply costs of renewable electricity.

The differences in deployment pathways are – in part – influenced by the differences in investment costs (Figure 36 for on-shore wind power plants and Figure 37 for solar power plants). Most notably the investment costs in all scenarios, except the High scenario, feature substantial cost reductions. The cost increases in the High scenario are motivated by the overall SSP3-type scenario derivative of low support for renewables, including subsidies and regulation, that increase the costs. Moreover, lower demand worsens the capacity factors of equipment suppliers leading to an up-wards pressure in supply costs (i.e., investment costs or power producers).

Figure 36: Investment Costs for on-shore wind

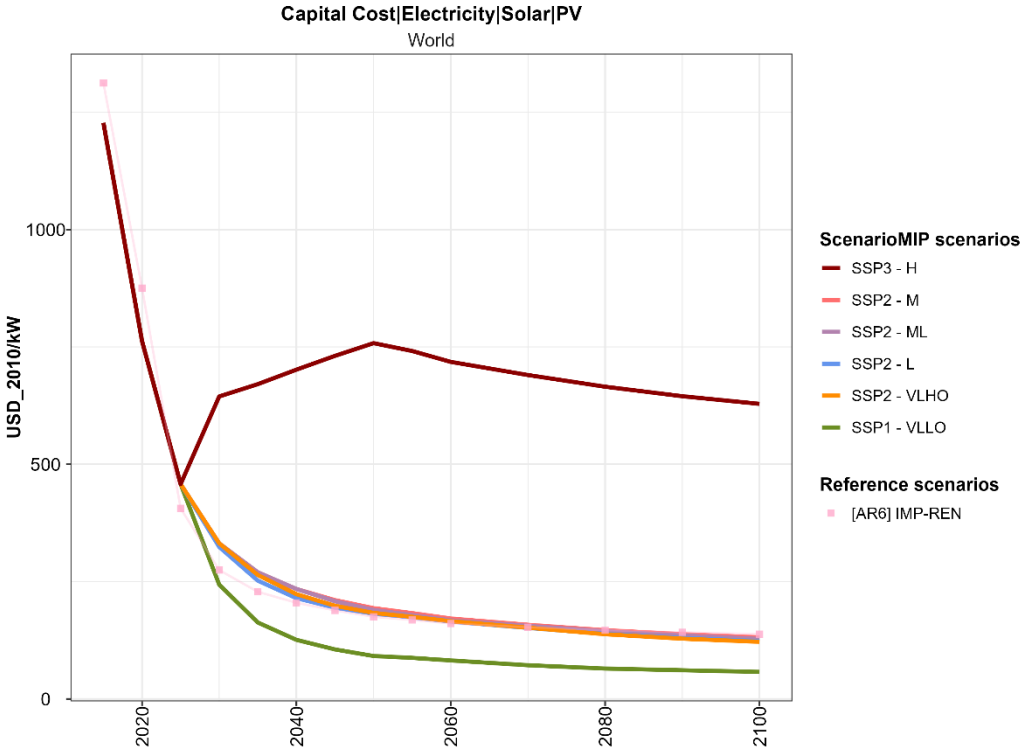
The figures show turn-key investment costs including the interest during construction. The figures do not include additional investment costs for the system integration.



Source: own calculation.

Figure 37: Investment Costs for solar PV

The figures show turn-key investment costs including the interest during construction. The figures do not include additional investment costs for the system integration.



Source: own calculation.

In comparison with the previous edition of SSP scenarios the base year investment costs as well as the long-term development are more optimistic (Krey et al. 2019) driving the robust growth of renewable electricity capacity expansions. Even the cost increases for Solar PV in the High scenario are not discouraging the growth, which is a crucial difference compared with the original edition of the SSP3 and SSP5 scenarios (Bauer et al. 2017).

6.6 Land-Use Change

In general, we observer large differences in land-use patterns between scenarios shown in Figure 38.

Forests and other natural lands suffer great losses in the H and the M scenarios due to not strengthened land-use regulatory policies (no GHG price on land-use change (LUC) emissions). The reason for the particularly strong losses in the H scenario (640 Mha of forest and other natural lands, which is 1.5 times the total land area of the EU) are a complete policy rollback (abolishing NPi policies) and the high population numbers of the SSP3 scenario especially in developing and emerging economies (see Section 6.2.1 and Popp et al. 2017). In contrast, forest area increases in the L, VLHO and VLLO at the expense of pasture area. Here by far the largest effect is observed in VLLO (plus 630 Mha) due to lower population (SSP1) and dietary shifts (low meat consumption) that free up agriculturally used area. The main driver in all low scenarios is a GHG price on land-use change emissions, which effectively protects carbon rich ecosystems. In line with the narrative, we observe a trend reversal in the ML scenario – first forest loss, then regrowth – due to climate policy starting only in 2040.

Crop and pasture areas are replaced by forests or the other way around, depending on the scenario. In H, crop area increases substantially (+580 MHa until 2100) driven by higher population (SSP3) and missing land regulatory policies (not driven by bioenergy). In the VLLO scenario pasture area is substantially reduced (by more than 600 Mha until 2070) and even total crop area decreases (minus 260 Mha total crop area, mostly until 2070), despite increasing bioenergy cropland by almost 150 Mha. The reason again are shifts towards low-meat diets.

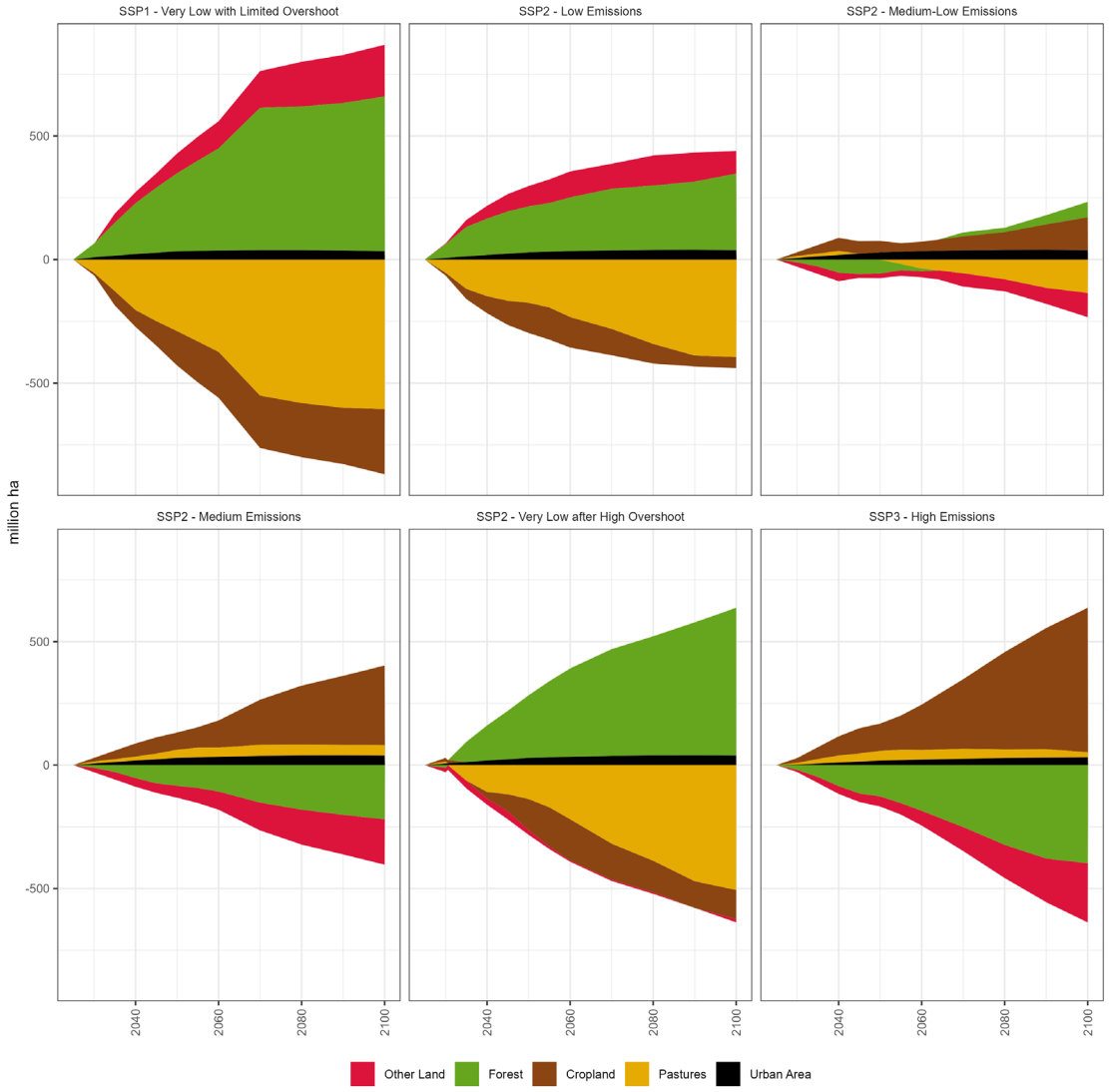
Investments into agricultural R&D lead to crop yields increases, which are driven and are accelerated by a combination of 1) avoided deforestation and afforestation via an AFOLU carbon price on land that reduces the potentially available agricultural area and 2) mitigation policy driven increases in bioenergy demand. For instance, large quantities of bioenergy crops (over 250 EJ/yr in 2100) in the VLHO scenario require substantial yield increases: average cereal yields more than double between 2025 and 2100, while dietary shifts in VLLO + SSP1 population require only very moderate yield increases. Interestingly, in the H scenario with high population growth yields increase only moderately. The reason is that the missing land regulatory policies allow for an unimpeded extension of crop area into natural lands.

The loss of forests and other carbon-rich ecosystems leads to large LUC-induced CO_2 emissions in the H scenario due to the rollback of climate policies. All other scenarios reduce net LUC emissions and (also except the M scenario) reach net negative emissions eventually. CDR from afforestation is highest in VLHO with CO_2 uptake by managed forests and harvested wood products exceeding 5 Gt CO_2/yr after 2055. The reason, why CO_2 uptake is highest in that scenario are specific assumptions on forest types. While in all other scenarios afforestation activities are assumed to resemble tree growth of natural forest to limit impacts on biodiversity, in the VLHO scenario with relaxed sustainability constraints afforestation activities can harness forest plantations with higher growth curves.

In the scenario with medium emissions (M) the updated SSP2 population projections (higher population in developing countries and emerging economies compared to SSP2-45, especially in

Sub-Saharan Africa) lead to higher food demand in low yield regions. On the other hand, reduced income growth projections slow down the move towards meat-rich diets. Since both effects have opposing effects on cropland requirement, the total crop area trends are similar in both scenarios.

Figure 38: Global land-use change compared to base year



Source: own calculation.

In the scenario with high emissions (H) population is higher now (up to 13 billion people by 2100) compared to the AR6 high emission SSP5-Baseline scenario (peak below 9 billion people). This leads to substantially more land area that is converted to cropland, such that CO_2 emissions from deforestation are at a high level throughout the whole century, while they drop to zero by 2060 in SSP5-85, where less crop area is needed.

At the low end of the emission range, we observe that the VLLO scenario has an even lower demand for cropland, while forest cover is higher than all AR6 scenarios due to dietary changes in combination with low SSP1 population.

The scenarios that heavily utilize bioenergy (L, ML and VLHO) still reach substantial levels of up to 270 EJ/yr. Yet, these levels are below the numbers of the scenarios with highest bioenergy

demand in AR6 (400 EJ/yr in 2100 in SSP1-19 and SSP2-45), since sustainability limits were more prominently put into the focus in the new scenarios.

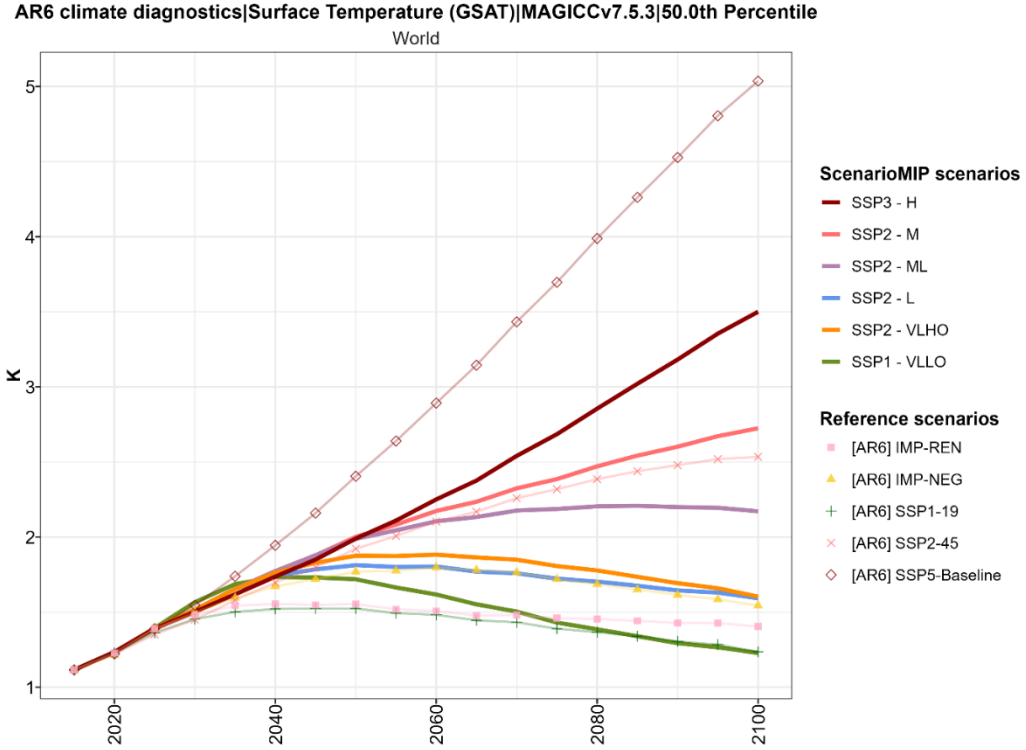
6.7 Temperature Outcomes derived with MAGICC tuned to CMIP6

Figure 39 shows the temperature outcomes. The most notable difference between the new generation of ScenarioMIP scenarios and key scenarios from the AR6 is the much weaker warming expected on the high-end scenarios. While the previously warmest scenario (SSP5-Baseline, equivalent to SSP5-RCP85) projected a full 5K of median warming by the end of the century, the warmest ScenarioMIP scenario assessed with REMIND-MAgPIE (SSP3-H) leads to a still strong but much lower warming of 3.5K in 2100.

This apparent relative optimism is largely due to the faster than expected observed reductions in the cost of renewables, updated assumptions on CDR technologies and to the implementation of some level of climate policies that, even if rolled back as in the SSP3-H scenario, already had some effect in the years between the assessments.

Figure 39: Global Mean Temperature for set of ScenarioMIP scenarios

Median (50th percentile) global mean temperature (GSAT) change relative to the pre-industrial period (1850-1900) evaluated with the AR6 climate assessment methodology (using the MAGICC model v7.5.3). As part of the ScenarioMIP process of information exchange between IAMs and ESMs, some changes in this methodology are to be expected before the AR7/CMIP7 final results, with likely minor changes to warming values as shown here. See Section 5.5 for more details on the current methodology and expected changes. Global Mean Temperature for set of ScenarioMIP scenarios



Source: own calculation.

On the lower end, however, the newer sustainability scenario (SSP1-VLLO) reaches a similar level of median warming (~1.25 K) than the low warming AR6 "Sustainable Development" (IMP-SD) and "Low Energy Demand" (IMP-LED) scenarios. This is despite the later starting point, committed emissions, and substantially stronger inertia that make SSP1-VLLO around 0.2 K warmer than those 1.5-compliant AR6 scenarios, and that leads to a similar magnitude overshoot of the target, highlighting its stronger reliance on net-negative technologies.

Another key distinguishing feature of the new generation of scenarios is the explicit exploration of the overshoot dimension, with scenarios that attempt to be in line with the 1.5 K target with higher (SSP2-VLHO, 0.4 K) or lower (SSP1-VLLO, 0.2 K) overshoots. The Very Low after High Overshoot (SSP2-VLHO) in fact does not return to below the 1.5 K target in this century, although it reaches 2100 with a cooling trajectory due to relatively strong net-negative CO_2 emissions.

7 Summary and Future Research Needs

The new ScenarioMIP scenarios constitute a major input to CMIP7. The process is not yet finished and at the time of writing this final report final steps are taken to round-up the contribution of the Integrated Assessment Model (IAM) community.

The REMIND-MAgPIE model developed and operated at PIK contributes to the ScenarioMIP process. This continues the efforts undertaken to deliver socioeconomic and technoeconomic scenarios of emissions and land-use to the ScenarioMIP process within CMIP6 that took advantage of the (then) newly developed Shared Socioeconomic Pathways (SSPs) by the IAM community. The ongoing round of ScenarioMIP updated the assumptions for the scenarios and applied the latest model versions. Updates include assumptions of demographic dynamics and economic growth as well as demands for energy, materials and food as well as specific technoeconomic data and emission factors of air pollutants and non-CO_2 GHGs. In the case of REMIND-MAgPIE the model updates include substantial improvements in energy supply and demand sector modelling, broader representation of the CDR portfolio, improved representation of land-use systems such as forestry and peat-land. Also, the interface with Earth System Models and Impact Models has been improved so that REMIND-MAgPIE is better equipped to deliver input data to other models, including the analysis of non-climate related Planetary Boundaries and Sustainable Development Goals. Finally, the policy representation of status-quo policies as well as future policies has been improved to better consider equity and fairness concerns. This comprises input assumptions as well as the quantification of distributional impacts.

Although not finished, preliminary and provisional results of the REMIND-MAgPIE model indicate that the new set of scenarios will show some substantial differences compared to CMIP6 that are important for further research and bear a number of policy implications. The provisional results of REMIND-MAgPIE scenarios indicate that the major differences compared with CMIP6 are and the tentative policy implications:

1. In recent years emissions did not follow the high scenarios, but were closer to the medium range of a SSP2-RCP4.5 scenario. The continuation on the Medium emission pathway will exceed the climate guardrails set by the Paris Agreement.
2. It is likely that high emission scenarios change substantially. GHG emissions reached in 2100 will be considerably lower and, consequently, the expected temperature increases will be lower. Major reasons are the structural changes in energy supply and demand towards higher electrification and renewable electricity production.
3. Low-end scenarios show that the emission reductions prescribed until 2025 in RCP2.6 and RCP1.9 equivalent scenarios have not been realized. Substantial emission reductions can now only be achieved post-2025. The delay in emission reductions can be catched-up and annual emission levels can be reduced to similar levels until later in the 21st century, but it is very unlikely that temperature increases beyond 1.5°C plus 0.1°C overshoot margin can be avoided. Therefore, it is very likely that the criteria for the C1 class of emission scenarios will not be met anymore. Consequently, a new target benchmark needs to be chosen to replace C1 (e.g. in GST-1, #27).
4. Also, land-use change shows similar patterns in the High emission scenario with lower losses of forest and other natural land in 2100, which is strongly related to lower population projections in the SSP3-type scenarios. In the very low scenario with only a low overshoot increases in forests and other natural land are greater than in the previous SSP1-26 scenario. This is mostly caused by change in dietary choices towards reduced meat consumption.
5. CDR deployment in the near-term is relatively similar in the cluster of low scenarios reaching 6-7 $GtCO_2$/yr by 2050, including increasing carbon stocks in wood plantations.

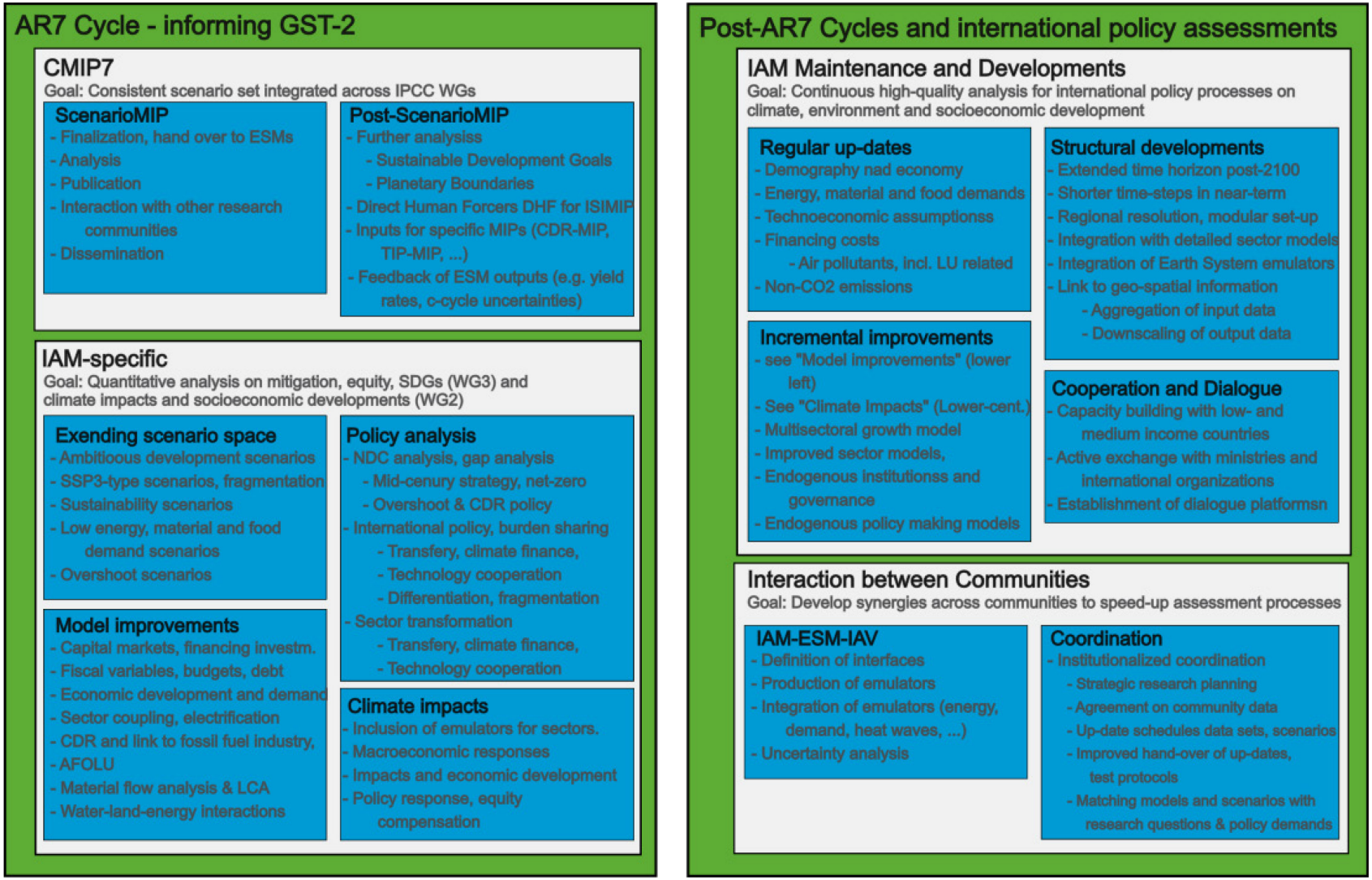
While the VLLO scenarios stay below 10 $GtCO_2$/yr the Very Low scenario after High Overshoot (VLHO) reaches annual removals of more than 25 $GtCO_2$/yr by 2100 due to strongly increasing CO_2 prices featuring heavy reliance on technical CDR options that inject CO_2 into geological storage sites.

The reduction of emissions and extensive agricultural production in the High scenarios compared with the original SSP5 and SSP3 scenarios is due to long-lasting changes in technologies such as electrification and renewable electricity as well as substantially lower population projections in the High scenario (here the SSP3-type of scenarios). Very-low emission scenarios are achievable due to a combination of lower material demands, such as living space and transport service demand, and improved technologies in all sectors. This includes heat pumps, battery electric vehicles and decarbonization of industrial processes combined with improved potentials for renewable electricity production, but also increased recycling systems for steel, and other bulk materials. These transformative changes reduce residual demand for fossil fuels and bring down gross CO_2 emissions. In the land-use sector the transition towards low meat diets is crucial to reduce CH_4 emissions and also to lower the demand for agricultural land, which facilitates land-based CDR. If these transformative changes in the energy, industry and land-use sector are more difficult to achieve, breakthroughs in CDR technologies are achieved and policy makers implement appropriate governance systems delayed, but rapidly strengthening climate policies $_2$ in the VLHO scenario could ramp-up CDR after 2050 to offset gross emissions and bring temperatures back close to 1.5°C by 2100.

This new set of ScenarioMIP scenarios provides answers to fundamental questions of transformation pathways and mitigation policies. The ScenarioMIP framework needs to be further developed to serve more specific scientific purposes and address demands from policy makers and make it fit for the coming challenges. This requires a strategic vision for future research. Figure 40 maps out the overall structure combined with more details at the strategic research level to build the integrated scenario framework in the ongoing Assessment Process of the IPCC and improve it for future Assessment Cycles for the IPCC and make it applicable to vital research and policy challenges related to environment and socioeconomic development. The strategic research vision comprises the needs of IAMs, such as REMIND-MAgPIE, but also the integration and coordination with researchers of the Earth System Model community and the Impact Model community.

The results of the ScenarioMIP effort aim to inform the ongoing Seventh Assessment Report (AR7) cycle of the IPCC and specifically the Second Global Stocktake (GST-2). The scenarios are the starting point for future research that integrates with other scientific communities connecting with CMIP7 (WG1) and ISIMIP (WG2) and also aims at more in-depth analysis of transformation dynamics and climate mitigation policies. The ongoing ScenarioMIP process initializes the integrated framework for future Assessment Cycles to inform future IPCC reports. This framework can – as whole or in part – serve as a tool to inform other political processes in the domain of environmental issues and socioeconomic developments.

Figure 40: Strategic research requirements for AR7 and post-AR7



Source: own compilation.

The ScenarioMIP scenarios will be evaluated by Earth System Models and Impact Models to provide a more integrated perspective about the consequences for climate change and adaptation potentials, which are also a crucial topic in GST-2. While most interfaces between IAM and ESM are already established, a more urgent challenge and, therefore, promising field of research is the interfacing with Impact Models via Direct Human Forcers that affect vital impact sectors and systems along with climate change. Also, the feedbacks from climate change and impacts to the socioeconomic systems will grow more important to fully close the loop. Despite the direct link to WG2 the modelling and analysis is more specific to IAMs. This link will be very important to bring in the benefits of avoided climate change and connect it the mitigation side of international climate policy.

Additional IAM-specific model development and analysis is necessary to gain insights into the feasibility of specific scenarios such as the Very Low with Limited Overshoot scenario. Policy makers will raise concerns whether strong near-term emission reductions are technically feasible and refer to potential trade-offs and synergies with socioeconomic development objectives in developing and emerging economies. Financing transformative investments is of a special concern for developing and emerging economies as their primary objective is economic development. Due to the global coverage IAM models can provide highly detailed information for varying assumptions on the implementation of the principle of "Common but differentiated responsibilities" and the choice of international climate finance. Research focusing on the many and diverse details of the transformation pathways is crucial to inform about the global and long-term objectives and the balancing with development and equity issues. These questions are expected to be at the core of debates on transformation targets in the run-up to and in the negotiations of GST-2 as well as future NDC updates. Finally, the scenarios can be used to evaluate the implications for Planetary Boundaries and Sustainable Development Goals (SDGs).

The shortening of the time frame for the Seventh Assessment cycle exerted substantial pressure on all IAM teams (including the REMIND-MAgPIE team at PIK) to contribute to ScenarioMIP. The team developed scenarios with the most up-to-date information and reflecting key policy concerns, such as equity and preparing improved interfacing with modelling communities that inform WG1 and WG2 of the IPCC. The increased time pressure mobilized potentials to speed-up the process without compromising the quality and even facilitate key improvements such as the timely and tighter integration with the Impact Modelling community (WG2) that is of crucial importance for developing and emerging economies.

During this phase it became increasingly clear that future assessment cycles can profit from a more organized coordination because research activities of diverse, yet small number of research teams that contribute to a scientific common pool resources that is supposed to be accessible to the global research community. For the IAM modelling teams a better planned and implemented process to provide the scenarios relevant for the other communities would leave more time for the downstream processes in CMIP and ISIMIP and it would leave more time for the IAM specific studies. This requires dedicated resources for continuous updates and maintenance of model tools and datasets to guarantee a reliable information basis. This is facilitated by a better coordination within the community of IAM modelling teams as well as other communities that provide inputs to IAMs, such as demographic and macroeconomic assumptions, and use the IAM outputs, such as ESM and IM modelers. The coordination challenge is to provide clear understanding about commonly used data sets and formats, scheduling of update cycles, definition of interfaces, derivation of reduced form models (i.e., emulators), etc.

The various communities mostly organize their processes independently with a limited degree of coordination. The Earth System modelling teams contributing to WG1 feature the highest

level of internal coordination under the umbrella of CMIP that is part of the World Climate Research Program (WCRP) of the World Meteorological Organization (WMO). The modelling communities developing IAMs and Impact Models do not coordinate their research in such a formalized setting. An increasing degree of coordination could also improve funding that supports contributions to these common pool resources for research teams worldwide. These long-term research strategies need to address key topics and issues, but also structural model developments that constitute major efforts. This includes issues like the extension of the scenario time horizon beyond 2100. This does not only affect IAM teams but also teams that provide input assumptions such as economic growth and development. Strategic research planning provides important signals for major directions and objectives for a diverse set of researchers, funders and policy makers.

A key topic for international climate policy directions of Germany and Europe is the finer regional resolution with improved representation of medium sized countries, such as Indonesia, Saudi Arabia, Nigeria, Brazil, etc. PIK is in a unique position, since potentials, risks and opportunities of the German Energiewende have been investigated in-depth in the Ariadne project using the REMIND-MAgPIE model and collaborating with other German research institutions. The Ariadne project showed that low-carbon energy systems based on cheap electricity from renewables as well as deep electrification of energy end uses can be cost-competitive or even cheaper than conventional systems. Especially for fast growing emerging economies, the low-carbon innovation presents a major opportunity for leap-frogging to cheap, sustainable and low-carbon energy supply. However, renewables-based system require fundamental paradigm shifts in finance, systems planning and operation. An integration of the long-term decarbonization perspective and short-term operation of power systems is essential to understand solutions to renewable energy integration challenges and for building trust in the energy transition. Further, renewable energy systems are much more capital intensive than fossil-based ones, and therefore focus particular challenges in Global South countries with higher finance costs.

Increasing the national and regional focus also requires closer cooperation with partners in these countries and helps to build capacity and credibility of model-based policy advice. PIK cooperates with partners around the world. This network can be used, extended and improved by setting up structured exchange programs that improve modeling capabilities. Such strategic move not only improves science, but would also improve the credibility of scenario-based policy analysis of policy makers in partner countries and thus facilitates international policy discourse.

Model and scenario-based information systems are crucial components for formulating, communicating and negotiating policies. The First Global Stocktake has invited the scientific community and the IPCC to contribute to the Second Global Stocktake and beyond. To fulfil this mission continuous maintenance and improvement of the modelling tools is necessary. Similar to informing the climate policy discourse the same modelling tools can also be used to inform other important international policy processes related to socioeconomic development and environmental change such as biodiversity, marine systems.

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